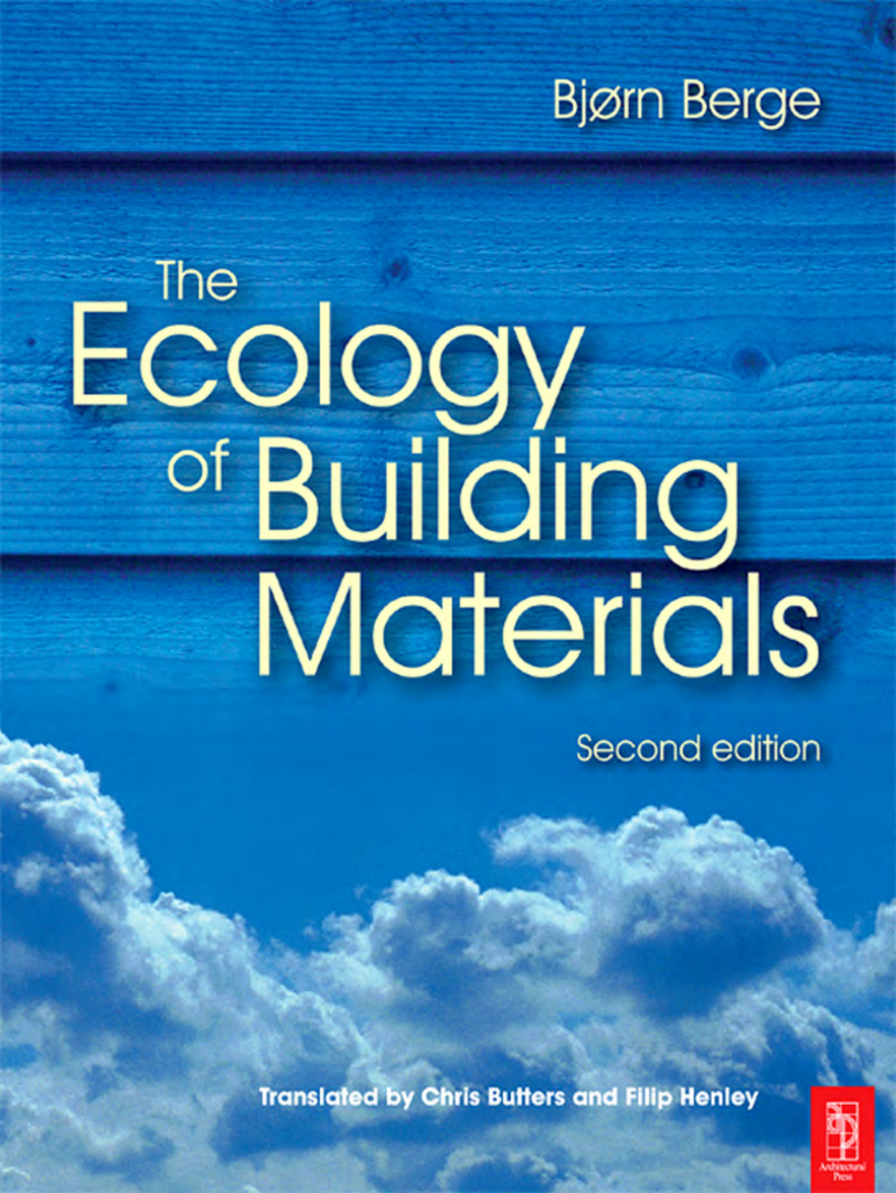

Bjørn Berge

The Ecology of Building Materials

Second edition

Translated by Chris Butters and Filip Henley

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To Dag Roalkvam, my enthusiastic and wise colleague through three decenniums

CONTENTS

Foreword to the Second Edition

The *Ecology of Building Materials* was originally published in Norwegian in 1992, and the first English edition appeared in 2000. The book you have before you now represents a comprehensive revision; it has been updated in the light of new materials, knowledge and practical experience accumulated during the past decade. If the quantity of information produced during these years is anything to go by, environmental questions have never been higher on the international agenda. The issue of climate change has played a central role, with successive and increasingly alarming reports from the International Panel on Climate Change (IPCC).

Whilst keeping to the same basic structure, the book has been considerably expanded. In particular this applies to climate related issues. The wealth of information now available has also made it possible to raise the general level of precision in many areas.

As with the previous edition, it is still the basic intention that this book shall serve as a reference book, rather than being read from cover to cover. Some overlapping and repetition has therefore been necessary.

Whilst Filip Henley translated the first edition, the translation of this edition has been undertaken by my colleague in Gaia Oslo, Chris Butters, whose knowledge and experience in the field of building ecology is exceptionally broad. He has also contributed with suggestions and additions that are integrated into the present text. My colleague Dag Roalkvam, also in Gaia Lista, has contributed similarly within the field of building physics where he is a recognised expert; and Rolf Jacobsen of Gaia Tjøme in the field of construction in straw and earth, one of his specialities.

I also wish to renew my thanks to others who have contributed to earlier editions of this work, including Frederica Miller, Howard Liddell, Varis Bokalders, Jørn Siljeholm, Hans Granum, Arne Næss, Karls Georg Høyer, Geir Flatabø, Per Richard Neeb, Odd Øvereng and Tom Heldal.

In this new edition, illustrations have been substantially upgraded and have been provided from many sources; in particular I wish to thank Anne Sigrid Nordby, Alice Reite, Rolf Jacobsen, Sergio G. Fox, Bertil Harström, Rod Ward Able, Dag Roalkvam, Camilla Høyem, Inga Lindstrøm and Anette Rosenberg.

Bjørn Berge
Lista, 2008

Introduction

> We cannot cure illnesses, but we can help Nature cure herself.
>
> Hippocrates

> I object! I do not agree that the Earth and everything that exists on her shall be defined by the law as man's living environment. The Earth and all that is hers, is a special being which is older, larger and stronger than us. Let us therefore give her equal rights and write that down in the constitution and in all other laws that will come... A new legal and moral status is needed where Nature herself can veto us through her own delegates... One must constitute the right of all things to be themselves; to be an equal with Nature, that is totally unarmed; do well out of it in a human way and only in accordance with their own nature. This means that one must never use a tree as a gallows, even if both its form and material fit the purpose excellently... What practical consequences should a law like this have? Before all economic considerations, this law would decide that nothing will be destroyed or severely damaged, all outstanding natural forms, landscape characteristics and naturally linked areas shall remain untouched. No economic or leisure concern shall be developed at the cost of nature, or worsen the living conditions of man and other beings. Everything that man wants to do in the future, he must do at his own cost and with his own strength. As a result of this law we may return to old methods of production or discover new ones which do not violate the law. The manufacturing society will crumble and multiply, the meaningless superfluity of similar products on the world market will give way to the local market, independent of transcontinental connections.
>
> Ludvìk Vaculìk, Czech author, in his essay *An alternative constitution*

The Greek terms economy, ecology and ecosophy belong together:

Oikos *House*
Nomos *Management*
Logos *Understanding*
Sofos *Wisdom*

If we consider the world to be our common house, we can say that we have managed too much and understood too little. In Nature – the existential base of humanity – the consequences of this are becoming clearer: melting of polar ice caps, desertification, diminishing biodiversity. These are things of which we are all aware. The growing incidence of stress and mental problems among the populations of industrialized nations would indicate that we have not even understood the nature of ourselves – that we, too, have become the victims of too much management.

Ecosophy expands the Kantian imperative 'to see every person as a goal, rather than a means', and to include other living beings. In this way, it defends the value of Nature in itself, and acknowledges that it is impossible to escape the third law of ecology: 'All things are connected' (Commoner, 1972).

We need a sustainable perspective of Nature that has a guiding influence on human activity or, alternatively, a general morality which is acceptable to all. The ecologist Aldo Leopold maintains: 'A thing is right when it tends to preserve the integrity, stability and beauty of the biotic community. It is wrong when it tends otherwise.'

This represents an ethic for which, in ancient times, there was no need. Trond Berg Eriksen (1990) describes the situation in antiquity:

> In antiquity, commanding the forces of Nature and bringing discipline to human nature were two sides of the same coin. In neither area did the interveners need to fear that they would succeed completely. The power of Nature was overwhelming. It took care of itself. Humans had to battle to acquire the bare necessities. Nature's order and equilibrium was unshakeable. Man was, and considered himself, a parasite on an eternal life system. The metropolis was a hard won corner, a fortified camp under threat from earthquakes, storms, drought and wild animals. The metropolis did not pose a threat to Nature, but was itself an exposed form of life... In such a perspective, technology was ethically neutral. Morality comes into play only when one can cause damage, in relation to someone or something that is weaker or equally strong. Therefore, the consequences of human actions for non-human objects lie beyond the horizon of moral issues.

Our ancestors' morality was based on the axiom that people themselves were the only living beings that could be harmed by human actions. Ethics focused on this; and ethics dealt with interpersonal relationships. At the same time this morality was limited to the moment – only the immediate consequences of an action were of significance. Long-term effects were of no interest and beyond regulation. Today, humankind's position and influence is drastically changed. The way in which we manage natural resources may have irremediable consequences for future generations of all life forms. Paradoxically, we still cling to antiquity's anthropocentric moral philosophy, often mingled with some of the Enlightenment's mottos of our sovereign supremacy.

'Four conditions to achieve a sustainable society', according to L.P. Hedeberg of the movement 'The Natural Step', are:

1. *Do not take more out of the crust of the Earth than can be replaced.* This means that we must almost totally stop mining and use of fossil fuels. Materials that we have extracted from beneath the Earth's surface (for example, metals, coal and oil) are difficult for Nature to renew, except in very small quantities. And that takes time. On the surface the rubbish pile gets higher because we have not followed this condition. Matter does not disappear; even if we reduce it to fine particles (by combustion, for example); it is only transformed into molecular waste. Every atom of a completely rusted car continues to exist and has to find a new home somewhere else. Everything may spread, but nothing disappears.
2. *Do not use man-made materials that take a long time to decompose.* Materials that Nature can break down and change into nutrients belong to the natural lifecycle. Many man-made materials, which have

never been a part of Nature, are very difficult for Nature to break down. Certain synthetic materials such as dioxins, DDT, fluorocarbons and chloroparaffins will almost never be broken down by Nature.

3. *Maintain the conditions needed for Nature to keep its production and its diversity*. We must stop impoverishing Nature through forest clearing, intensive fishing and the expansion of cities and road systems. The great diversity of animals and plants are a necessity for all life cycles and ecosystems, and even for our own lives.
4. *Use resources efficiently and correctly – stop being wasteful*. The resources that are available must be used efficiently and distributed fairly.

THE ECOLOGY OF BUILDING MATERIALS

Is it realistic to imagine a technology that is in line with holistic thinking whilst also providing humanity with an acceptable material standard of living? This book illustrates the role and potential of building materials in such a perspective. And, in the same context, to illuminate the following aspects:

- *Work*. The methods used to produce each building component. How production takes place and can take place.
- *Raw materials*. Occurrence of material resources, their nature, distribution and potential for recycling.
- *Energy*. The energy consumed when producing and transporting the materials, and their durability.
- *Pollution*. Pollution during production, use and demolition, the chemical footprint of each different material.

A primary goal of this book is to enable the various actors in the building industry to pose environmental requirements, and to do this with greater precision. In order to ensure an environmentally responsible building, it is important to obtain precise answers to questions such as ‘Is the steel produced in a blast furnace or an electric arc furnace?’; ‘Are pozzolanas used in the cement clinker?’; or ‘What kind of adhesive is used in the hemp matting, and how much?’. It is also hoped that the book will contribute towards reducing misleading advertising information. Green products are now much in demand, and many producers are claiming to fit this mould without apparent justification.

HOW TO USE THIS BOOK

The *Ecology of Building Materials* is an attempt to present the possibilities for existing materials, as well as evaluating new materials. A number of partly abandoned material alternatives have also been evaluated. In particular, we will look at vegetable products, often with traditional methods of preparation. In their present state these methods are often of less relevance, and these reviews must therefore be regarded as tentative.

Many factors relating to the materials discussed depend upon local conditions; this book is primarily based on the climatic and topographical conditions in northern and central Europe. However, when considering the Earth as a whole, it will become clear how little the overall use of materials varies; and the principles underlying better solutions to a large extent are universal.

The materials dealt with are those that are generally used by conventional builders such as bricklayers, masons, carpenters and locksmiths. Under this category, all fixed components and elements that form a building are included, with the exception of heating, ventilation and sanitary installations. Materials providing high environmental standards are presented most thoroughly, whilst less attractive and often conventional alternatives are given less attention.

The book is divided into three Parts:

Part 1: **Eddies and water-level markers**. *Environmental profiles and criteria for assessment* covers the tools which we shall use to evaluate and select materials on the basis of production methods, raw material availability, and energy and pollution aspects. Tables illustrate important alternatives available and key information on their environmental profile is presented. The information derives from many different, reliable sources, mainly European. They show quantifiable as well as qualitative environmental effects and should be read in conjunction with more comprehensive presentations in Parts 2 and 3. The final chapter in this section gives an introduction to the chemical and physical properties of building materials.

Part 2: **The flower, the iron and the sea**. *Raw materials and basic materials* presents the materials at our disposition. The term 'raw materials' denotes the materials as they are found in nature, either as a single chemical compound or as a combination of several compounds. They form the basis for the production of 'basic materials' such as iron, cement, linseed oil and timber. These materials form building blocks in complete products. The section is divided into chapters that present the different organic and mineral materials and discuss the ecological consequences of the various ways of utilizing them.

Part 3: **The construction of a sea-iron-flower**. *Building materials* discusses usage, such as roofing and insulation, and assesses the usability of the various alternatives from an ecological perspective. Descriptions are given of the practical uses of the best alternatives. This Part is divided into seven chapters:

1. *Structural materials* that support and brace.
2. *Climatic materials* that regulate warmth, humidity and air movement.
3. *Surface materials* that protect and shield structures and climatic materials from external and internal environments.
4. *Windows, doors and stairs*.
5. *Fixings and connections* that join different components.
6. *Paint, varnish, stain and wax* that improve appearance and provide protection.
7. *Impregnating agents, and how to avoid them*: the different impregnating substances and the alternatives.

The structural, climatic and surface materials covered in the first three chapters in Part 3 represent 97–99% of the materials used in building, and environmental evaluations are given for each. The evaluations are mostly based on information given in Part 1 of the book. In addition to conventional environmental issues, human ecological aspects are also discussed, primarily through questions such as the feasibility of local production of building materials.

The evaluation tables in Part 3 are ordered so that each functional group has a best and a worst alternative for each particular aspect of the environment. In the concluding summarized evaluation, priority is given according to the standing place of the author. In such processes, political, cultural and ethical aspects come strongly into play. In Africa for example, the raw material question is usually given high priority; in New Zealand and Argentina, factors that affect the ozone layer are taken very seriously; in Western Europe high priority is likely to be given to human toxicity. Today however, in most regions one is likely to find that global warming is the most important environmental parameter (Anderson, 2000; Lippiatt, 2007). A separate column in the tables is therefore devoted to the global warming potential (GWP) of each product. An added reason for presenting the potential climate effect of the products is that this often provides an excellent indicator of other environmental effects. A product causing high greenhouse gas emissions is very likely to be resource intensive and a source of emissions of other toxic chemicals and by-products during the production process. Studies show a clear correlation between climate-related results and results of broader environmental analyses (Strand Hansen, 2002).

It is necessary to emphasize that information provided in this book represents the state of our knowledge as of the date of publication. The sciences that address the different relationships in the natural environment are complex, relatively young, and in some cases just beginning. New aspects come to light continuously, some of which can affect the whole situation. An example is chlorofluorocarbons (CFCs), which were not considered to be a problem until the 1970s when their effect on the ozone layer became known.

It is also important to underline that the evaluations in this book are based on the precautionary principle. The consequences of using a material, in particular new products, should be well understood before it is taken into use.

It must be emphasized that the evaluation tables describe isolated materials, and not composite constructions consisting of several elements such as often occur in buildings. This may give a slightly distorted picture in certain cases; for example, ceramic tiles and the mortar or jointing mastic used with them cannot be considered independently. In most cases, however, the tables represent a thorough basis for comparisons between products at a fundamental level.

Life span evaluations of building materials

During the last 20 years many methods have been developed to evaluate the lifecycle environmental profile of building materials. After some years of trial and error, several of these are now useful and effective tools. Amongst those to be recommended are ENVEST (England), BEES (USA), ATHENA (Canada), EPS (Netherlands), BEAT (Denmark) and ECOPRODUCT (Norway). They are all based on transforming qualitative into quantitative data that are then collated into a final value expressing the environmental impacts of a material during its life span. Results for any given material may vary somewhat between systems because the evaluations are largely based upon prevailing national regulations presenting acceptable pollution limits, etc. Comparisons are further complicated by the fact that some systems weigh in economic factors, and that there is varying breadth in the environmental factors taken into consideration. The systems also have varying degrees of transparency, often including hidden evaluation procedures.

It is to be hoped that there will be an increasing degree of coordination internationally, especially in view of the global nature of the environmental issues at hand, in particular climate-related. A good degree of transparency is also important and the reasons for variations of a national character should be easily identifiable.

OTHER GUIDELINES FOR READING THIS BOOK

All products discussed in this book are in common use or have recently been used in the construction industry. It has been beyond the scope of this book to discuss the various national or supranational (such as the EU) regulations and restrictions on singular materials. This is also a complex field where new regulations and principles, not least relating to sustainability, are fast emerging.

Since the materials are arranged and discussed in groups, compound materials with components belonging to different substance groups will often be encountered, such as woodwool cement boards, made up of wood shavings and cement. In such cases, the product is listed according to which of its components has the largest relative volume.

There are also cases where a material has, for example, both structural and climatic characteristics. Such materials are included in the main summaries and tables in both of the relevant sections, but the main presentation is to be found where it is felt that this material best belongs.

A number of approaches and recipes for alternative solutions are described. In cases where no specific sources are mentioned, these are the author's own proposals, and have no legal or financial liability. In some cases, recipes with less well-documented characteristics are also presented in order to provide historical and factual depth.

Terms such as 'artificial', 'synthetic' and 'natural' are always somewhat controversial. In no way are these meant to imply an assessment of quality. All raw materials used are originally natural. In artificial/synthetic materials, however, the whole material or part of it has undergone controlled chemical and other treatment processes, usually involving high levels of heat. The extraction of iron from ore is a chemical process, whilst the oxidization or corrosion of iron by air is a natural process.

The definition of biogradability used in the book is limited to materials undergoing decomposition primarily through enzymatic action of micro-organisms to carbon dioxide, methane, inorganic compounds or biomass within a limited period of time. Photodegradation, oxidation and hydrolysis of, for example, synthetic polymers, are not regarded as biogradability.

The main greenhouse gases and toxic compounds are presented in Table 2.3 and Table 2.5 in Chapter 2. Here they are defined by their

Chemical Abstract Service (CAS) registry number, since several names are often used for the same compound. Compounds listed in these tables are given a grey colour when discussed elsewhere in the text parts of Part 2 and 3.

For the sake of readability, the extent of referencing given directly in the text has been limited to cases involving assertions and hypotheses that may appear surprising or controversial and therefore need to be documented in particular. A comprehensive list of suggestions for further readings is to be found at the end of each Part.

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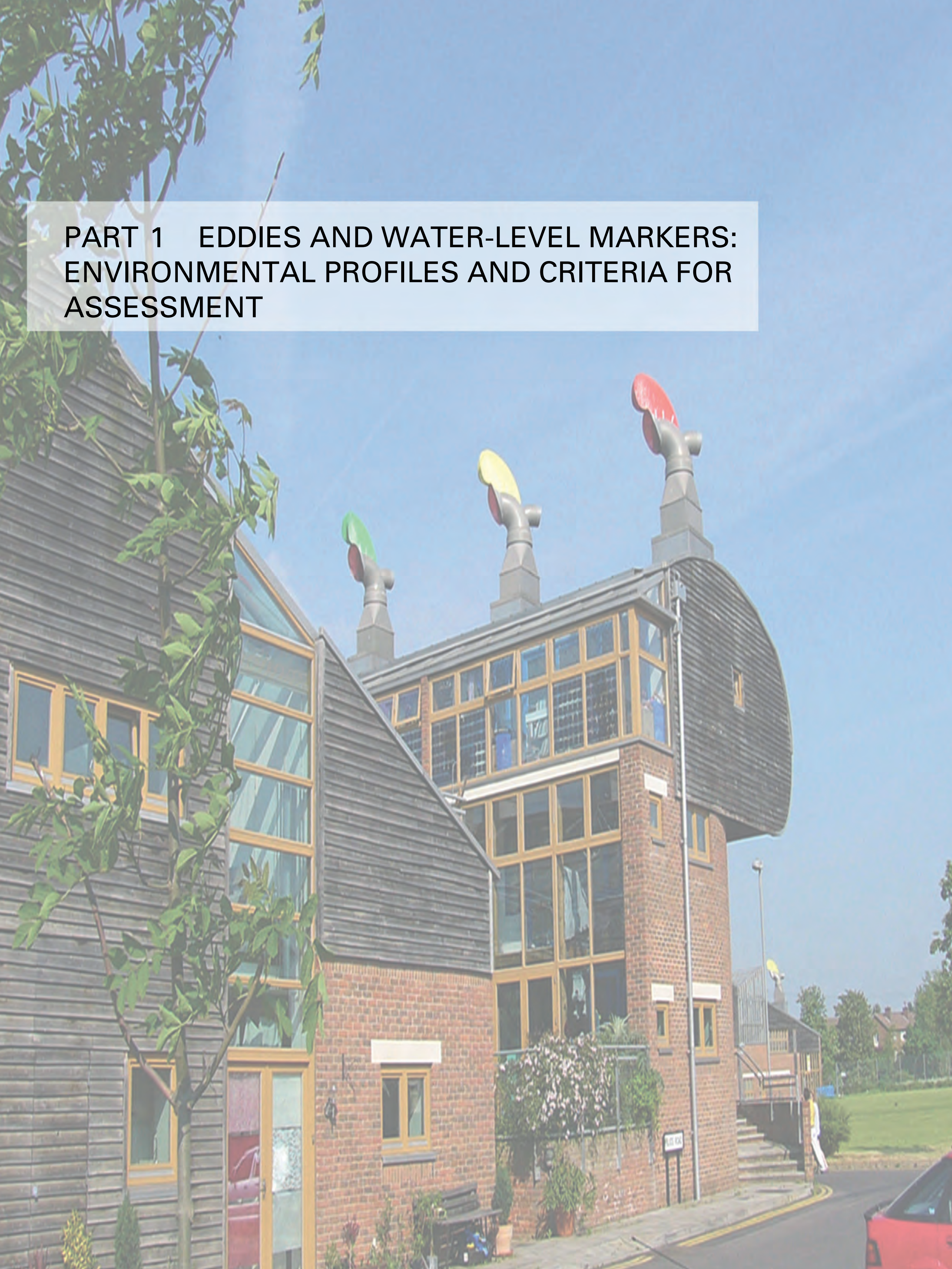
PART 1 EDDIES AND WATER-LEVEL MARKERS: ENVIRONMENTAL PROFILES AND CRITERIA FOR ASSESSMENT



1 Resources

Natural resources are usually defined as ‘renewable’ or ‘non-renewable’. The first are resources that can be renewed or harvested regularly, such as timber for construction or linseed for linseed oil. They are only renewable as long as the right conditions for production are maintained. Depletion of the ozone layer is an example of how conditions for many renewable resources can be drastically changed. Most renewable resources have photosynthesis in common. It has been estimated that human society currently exploits about 40% of the earth’s photosynthetic activity (Brown *et al*., 1990).

Non-renewable resources are those that can only be harvested once. These are often referred to as ‘stocks’ (iron ore is an example); or else resources that are formed extremely slowly, such as crude oil. Many of these are seriously limited; metals and fossil oils are the most exploited, but in certain regions even materials such as sand and gravel are becoming scarce. The approximate reserves of raw materials are shown in Table 1.1. It is clear that some of the most important resources are in danger of being exhausted in the near future.

Table 1.1 *Non-renewable resources used in the manufacturing of building materials*

Raw material		*Reserve [years]*	*Reserve base [years]*	*Annual growth in consumption 1999–2006 [%]*
MINERAL				
1	Aggregate (sand, gravel)	Very Large	Very Large	
2	Arsenic	20	30	6
3	Bauxite	141	180	6
4	Bentonite (Montmorillonite)	Large	Large	
5	Boric salts	35	86	1
6	Brom	Large	Large	
7	Cadmium	26	77	1
8	Chrome	Ca. 25	Ca. 40	8
9	Clay, for fired products	Very Large	Very Large	
10	Cobalt	121	226	15
11	Copper	31	61	3

Table 1.1 *(Continued)*

Raw material		*Reserve [years]*	*Reserve base [years]*	*Annual growth in consumption 1999–2006 [%]*
MINERAL (continued)				
12	Diatomite (silicious fossil meal)	Large	Large	
13	Earth, for compressing	Very Large	Very large	
14	Feldspar	Large	Large	
15	Gold	17	36	1
16	Gypsum	Large	Large	
17	Iron	95	219	10
18	Kaolin	Large	Large	
19	Lead	20	42	1.5
20	Lime	Very Large	Very Large	
21	Magnesium	Large	Very Large	
22	Manganese	40	472	9
23	Mica	Very Large	Very Large	
24	Mineral salt (sodium chloride)	Very Large	Very Large	
25	Nickel	41	90	5
26	Perlite	Large	Large	
27	Phosphate	124	345	0
28	Potash	Large	Large	
29	Pumice	Large	Large	
30	Quartz	Large	Large	
31	Silica	Large	Large	
32	Silver	14	29	3
33	Soda ash	Large	Large	
34	Stone	Very Large	Very Large	
35	Sulphur	21	53	1
36	Tin	22 (in 1999)	40 (in 1999)	4
37	Titanium	122	240	5
38	Vermiculite	Large	Large	
39	Zinc	22	46	4.5
FOSSIL				
40	Coal	150		4.5
41	Natural gas	63		3
42	Crude oil	41		1.4

Reserve is defined as that part of the reserve base that could be economically extracted or produced at the time of determination. *Reserve base* includes those resources that are currently economic (*Reserves*), marginally economic, and some of those that are currently subeconomic. Both *Reserve* and *Reserve base* are estimated without growth in consumption. To sharpen the scenarios the annual growth in consumption 1999–2006 for the raw materials most threatened by depletion is also shown (U.S. Geological Survey, 2000 & 2007; British Petroleum, 2007)

Fresh water is a vital resource which cannot be described as either renewable or non-renewable. The total amount of water is constant in a global perspective; but on a regional level, shortages of water are already critical, and likely to become more so given climate change. This is especially the case for potable water, which is essential not only in food production but also in many industries. Water is often used in industry in secondary processes; for example, as a cooling liquid, which is then returned to nature polluted and with a lower oxygen content.

Biodiversity and fertile soils are also to be seen as resources in the global ecosystem; and they too are only conditionally renewable. Their rate of exploitation or depletion is now in some cases so rapid that there is a danger that critical thresholds will be crossed (Müilerman and Blonk, 2001). This is closely linked to both increased extraction of resources and increased water use. Research based on measurements of the loss of forest area, freshwater and marine species, indicates that the 'health' of the world's ecosystems has declined by 30% in the past 25 years (WWF, 1998).

USABLE AND LESS USABLE RESOURCES

It is also common to classify resources into 'usable' and 'less usable'. The earth's crust contains an infinite amount of ore. The problem of extracting it is a question of economy, available technology, effects on the landscape and environment and energy consumption. At the beginning of 1900 it was estimated that, for a source of copper to be exploitable there should be at least 3% copper in the ore; by 1970, the level had fallen to 0.6%. Resources that have been uneconomical to extract in the past can become a viable proposition; this is both due to rising value and better extraction technologies. For example, a more efficient technology for stone extraction would give this material a fresh start for use in construction. The sum of usable and less usable resources is also called the 'reserve base', whilst the usable resources are called 'reserves'.

There are also cases where economic conditions and developing technology have a negative impact on the extraction of raw materials; for example, technical mechanization in the timber industry has made hilly forests inaccessible. Only by using a horse or other small-scale equipment should timber be retrieved from such a forest, but this is rarely the way of the modern timber industry, despite the fact that it causes the least damage to the forest. In the same way, modern technology cannot cope with small deposits of metallic ores – modern mining needs large amounts of ore to make it economical.

Political situations can also affect the availability of raw materials. The civil war in Zaire increased the price of cobalt by 700%, as Zaire has the world's largest deposits of cobalt. Similarly, the situation in the Persian Gulf has affected the price of oil for many years. The United States Department of Domestic Affairs has made a list of 'critical minerals'. In addition to cobalt it includes bauxite for aluminium production, copper, nickel, lead, zinc, manganese and iron; in other words, quite a few of the most important metals (US Congress, 1983).

USED AND UNUSED RESOURCES

Resources can also be categorized as 'used' or 'unused'. The total number of different plant species for all of Scandinavia is about 1500. Of these only two to three are widely used for building, 10 are used occasionally, whilst some 60 further species have potential for use.

A further example is flint, which was once amongst the most important resources available, but is virtually left unused now. Similarly, it can be said that in 1840 oil was an almost totally unexploited 'non-resource'.

In 1933 the geographer Zimmermann stated: 'Resources are not anything static, but something as dynamic as civilization itself'. However, this statement does not offer us much ground for optimism. With accelerating rates of exploitation, we are on the verge of bankruptcy in many important raw materials (Weiszacker, 1998; Rodenburg, 2000). Those at a real risk of exhaustion are mineral ores and fossil oils; but for several renewables, prospects are not good either. Problems related to tropical timber are well known, and discussions centre around the effect of different forms of management, tax rates, replanting, etc. Conditions for the renewability or failure of important biological resources are very likely to change quickly as a result of increased climate change, in particular alterations in temperatures and precipitation.

It is quite absurd that our planet's stocks of raw materials should be stripped and disappear in just a fraction of the time-span of human existence – whether by that we mean two, ten or fifty generations. Even a traditional 'anthropocentric' morality with a limited time perspective requires that use of such raw materials be allowed only in special circumstances, and that recycling should be mandatory.

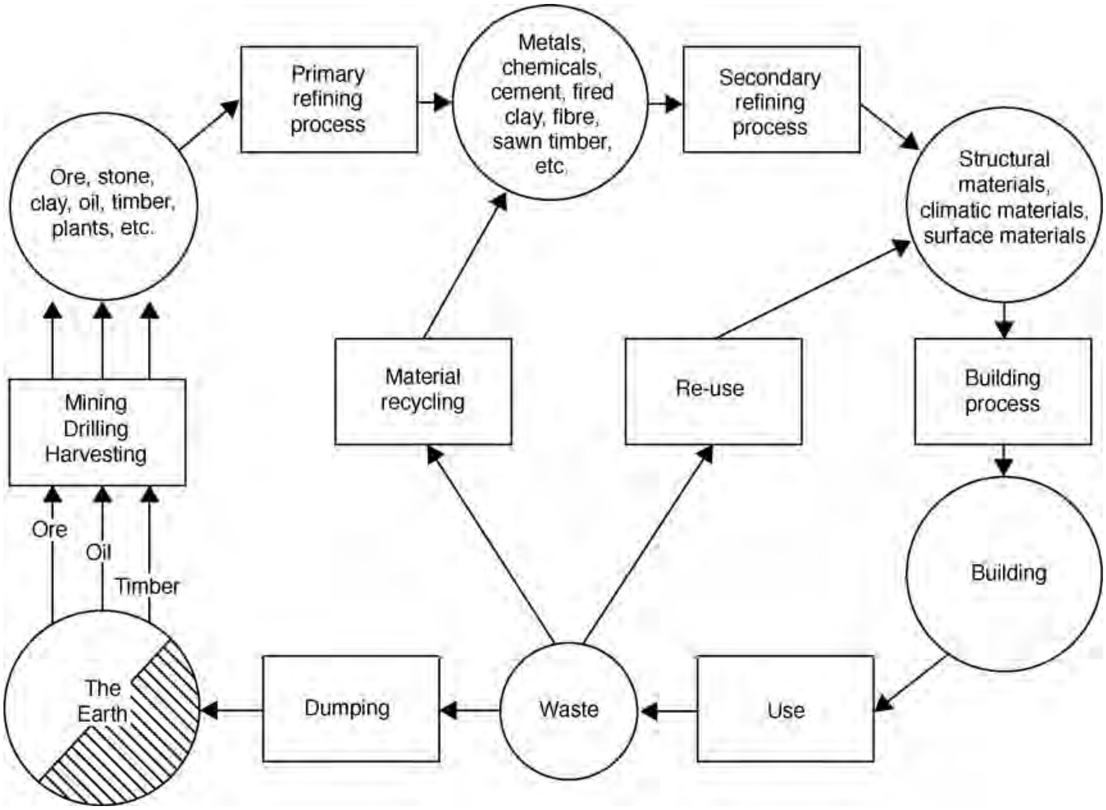
A differentiation is also made between *material resources* – the actual constituents of a resource and *energy resources* – the type and amount of energy needed to produce the material.

1.1 MATERIAL RESOURCES

The building industry is, after food production, the largest consumer of raw materials in the world today. A broadly accepted goal for a sustainable future is a drastic reduction in the use of raw materials. This is most important for the scarce non-renewable resources but also for the others; partly because it is the *throughput* of materials in the economy that is linked to major energy and environmental loads. Equally important is reducing wastage and losses during production, the construction process and throughout the life of the completed buildings. The recycling of materials following demolition must also become the rule. Recycling processes should also ensure that materials can be taken care of at their original level of quality, rather than downcycled.

1.1.1 Actions for resource conservation in the production of materials

Change-over to exploitation of smaller deposits of raw materials
This is mainly a question of technology. Even though modern technology is primarily geared to large-scale exploitation ('economies of scale'), viable smaller-scale alternatives often exist. Small-scale exploitation is often far less damaging to the environment, in particular as regards water resources and biodiversity.



1.1

The cycle of materials.

Greater attention to unused resources and waste products

Many resources that were formerly classified as 'uneconomical', and now fallen into disuse, and others that have not previously been used, need to be studied. Examples of such resources are compressed earth used as a construction material; fibres from the seaweed eelgrass as an insulating material; and increased use of timber from deciduous trees.

The same applies to an increasing number of 'waste' products from industry, agriculture and dwellings, such as straw, fly ash, industrial sulphur and waste glass.

Substitution with less limited types of resources

Many raw materials are not in danger of exhaustion in the foreseeable future. An example is stone, which is still plentiful in most places. Another is blue clay, which has great potential and is in no way near being exhausted by the small existing production of clay bricks.

Substitution with renewable resources

Many building components currently made from non-renewable raw materials have renewable alternatives. For example, timber can be used as an alternative to steel. A wide range of plastics can be produced from plants instead of fossil hydrocarbons. This type of substitution will usually have a positive overall environmental impact.

However, we must beware of the risk of increased use of renewable resources in construction coming into conflict with food production. Seen in the global perspective, with a rising population, one should give first priority to waste products from agriculture and plants that can be grown in relatively unproductive land areas – as is the case with most timber species.

Increased recycling of waste products during production

For reasons of simple efficiency and cost, many good examples, showing how the recycling of waste products during production can save valuable resources, already exist. For example, in the plasterboard industry today waste has nearly been eliminated in the production process. Re-use of water in the production processes of certain industries also occurs more often; for example, in the production of ceramic tiles and wood fibre boards.

1.1.2 Reduction of the use of materials in the building

'Do we really need to build this at all?' should be a basic question if one wishes to reduce the use of resources in construction. It is, however, seldom appreciated by any of the parties involved in design processes. The obvious second question is then 'How can we reduce the need for materials?', and here a whole range of possibilities emerge.

Reduce the need for materials, adaptable buildings

Space use per person has doubled in the western world since 1960. In housing, each of us now consumes 40 to 50 square metres (Berge, 2003). This implies an approximate doubling of the consumption of materials. At the same time, both housing and other types of building have become more specialized, being tailored and optimized for specific functions. In most cases they are becoming far less flexible or adaptable.

This static approach, in a society characterized by rather rapid changes both in cultural patterns and technology, means that buildings are often demolished well before their intended lifetime is over. Initial lifetime projections (service life predictions) are often incorrect. In Sweden, 25% of the buildings that have been demolished since 1980 were less than 30 years old (Thormark, 2007). In Tokyo the average lifetime of a building has been as low as 17 years in periods of high economic activity (Brand, 1994). Expected climate changes will make this picture even worse. Considerable areas of land may become uninhabitable due to sea level rises as well as increased risks of flooding and landslides. Higher temperatures may increase the need for solar shading, cooling technology and insect protection measures, all requiring building modifications or replacement. Increased precipitation or more frequent temperature variations may also lead to accelerated decay of building envelope materials.

Our response to these scenarios has to be a requirement for buildings that have an increased adaptive capacity. This relates not only to the technical systems, but also to planning aspects, where the following principles need to be addressed:

- *Generality*: spaces allowing for a broad range of activities.
- *Flexibility*: buildings permitting easy changes to floor plans as well as to the technical systems.

- *Elasticity*: designs permitting expansion as well as contraction of buildings. Extreme elasticity implies buildings with short lifetimes of say 10–15 years that can be easily dismounted, reprogrammed and reassembled.

All the above necessitate new and appropriate design and construction methods, in order to allow for change and the avoidance of extensive waste of materials usually associated with the modification and demolition of buildings.

It has been estimated that such solutions can increase real building lifetimes by 25% in 25% of all buildings (Kram, 2001). Optimizing buildings in this way also reduces overall space needs and therefore also the energy consumption for heating, cooling, lighting and ventilation. This kind of approach is probably more efficient than today's conventional approach of reducing energy use by superinsulation, solar panels and heat pumps.

Economical use of materials

Any given structural system requires a specific amount of materials, and the difference between systems can be quite significant. As the best engineers know, the amount of material used in a steel column can be reduced several times by optimizing the design; and a lattice beam uses much less material than a solid beam, whether it is timber or steel. Other typical examples are hollow bricks and aerated concrete blocks instead of massive products. Again, due to increasing resource and cost constraints this kind of efficiency is in full progress.

A choice of lightweight constructions rather than heavy alternatives, such as timber instead of concrete, also significantly reduces the need for foundations. On difficult sites such as waterlogged or clay areas, it has been calculated that the use of a lightweight construction can reduce the use of concrete footings from 250 to 150 kg/m^2 (Gielen, 1997).

Minimizing materials losses and wastage on site

Every material has a 'loss factor', which describes how much of a particular material is typically lost during storage, transport and installation of the final product.

Loss of materials on site is approximately 10% of the total waste in the building industry. This can be halved with carefully planned site management (Thonvald, 1994). Timber and other off-cuts can be sorted and re-used elsewhere. Using loose fill insulation avoids the often considerable wastage of insulation off-cuts. Prefabrication provides even greater savings, where almost all wastage can be eliminated either through pre-cut components or prefabrication of whole elements. In Scandinavia today almost 80% of all new housing units are produced off-site. One should remember, however, that some prefabrication systems necessitate extensive use of jointing mastics or gaskets that may have unfavourable environmental characteristics.

Within the building industry, a great deal of packaging material is used during transport and for storage on site. Some packaging serves no greater purpose than to advertise the name of the supplier. If nothing else, packaging should be easily recyclable and therefore should not comprise materials such as aluminium and plastic composites.

Loss of material caused by wear and tear in the completed building will also occur. The Swedish Department of the Environment estimated in 1995 that the loss of copper from roofs and pipes through weathering amounted to more than 1000 tons per year. In addition to the resulting pollution, this represents a large loss of resources. Materials based on rare, non-renewable resources should thus preferably not be used in exposed parts of the building.

Use materials in ways that ensure their durability

It is important to match the resource quality to the task required, so as not to use a high-grade resource when a lower grade one will suffice. But it is still a general rule that by producing more durable products the use of raw materials is reduced. However, one must ensure that materials of similar durability are used throughout the vital parts of a building; therefore not sacrificing high quality components due to rapid decay elsewhere. Lower quality materials should be used in such a way that they are easily replaceable, whilst more durable materials may be easily dismantled for re-use or recycling.

Simply put: twice as much damage to the environment can be tolerated for a product that lasts 60 years compared to one that lasts only 30 years. The lifespan of materials is governed mainly by four factors:

- *the material itself*, its physical structure and chemical composition.
- *the local environment*, climatic and other chemical or physical conditions.
- *the construction and its execution*, where and how the material is fitted into the building.
- *maintenance and management*.

The lifespan of a roof tile, for example, is dependent not only on the type of clay used, but also on the immediate environment of the building. A high moisture content in winter can cause frost damage even in high quality tiles. The best way to determine the real lifespan of a material is through long experience and concrete documentation. It is therefore difficult to anticipate the lifespan of many new materials, such as new types of plastics. It is possible to perform accelerated deterioration tests in laboratories, but these generally give a simplified picture of deterioration processes, and results can only be taken as approximate.

During construction, many materials are exposed to rain or humidity. Sealing damp materials into buildings is a principal cause of subsequent defects, as well as posing a well-documented health risk. Adjoining building components may also be damaged. Careful site management routines and storage are recognized today as an important preventive solution. Other solutions include construction systems where the load bearing structure and roof covering are assembled first, and construction canopy systems, usually called Weather Protection Systems (WPS).

Construction systems also need to protect materials during their lifetime from stresses (arising from within or without) such as undue temperature and humidity conditions. An important aspect of this is due adaptation to local climatic conditions, not always the case in an industry that uses standardized solutions regardless of regional climatic differences. This applies in particular to high value items such as doors, windows and balconies, as well as to appropriate roof detailing. A major investigation was made in 2001 of 16 000 buildings in Denmark, including single-family houses, apartment blocks, offices and schools (Valbjørn and Eriksen, 2001). It showed that buildings with flat roofs had twice as high a risk of serious humidity damage. Bathrooms with timber based wall and floor structures had twice as high a risk as those in masonry and mineral materials (see Figure 14.6 in Chapter 14).

In order to reduce energy consumption and climate emissions, most temperate and cold climate countries are introducing ever stricter norms for increased thermal insulation of buildings. In some cases, this has led to increased humidity damage – partly because less heat from inside the building actually leaks out into the walls to dry out any humidity that may have gathered there. This means that there is a higher requirement for precision in both the detailing and execution of highly insulated, low energy buildings. This will not be easy to achieve. For this reason it would be a major advantage if one can employ materials with good hygroscopic qualities – materials that can tolerate and regulate humidity.

We should also remember that durability is not only a quantifiable technical parameter. Durability also has an important aesthetic aspect. It is quite a challenge to design a product that can outlast the vicissitudes of both time and fashion.

On the other hand, there is a point where long-lasting buildings become an economic or environmental burden; it becomes difficult to upgrade or adapt them any further, and their replacement would save resources due to technological advances and efficiency gains. The resources saved by continuing to use an old, energy consuming building have to be weighed against the new materials needed to build a replacement building that can save much energy over the following 50 or 100 years. Comparative lifecycle assessments can be made to inform such decisions. The key question is thus optimum rather than maximum durability.

The decay of building materials is also a health issue. Decay of building sheets and tiles containing asbestos releases the toxic fibres into the environment; decay over time of bathroom boards exposed to prolonged dampness can also increase off-gassing and release of synthetic chemicals into the rooms. Material decay can also increase the danger of fungal growth and other harmful agents into the indoor environment, causing increased allergic or respiratory ailments.

DURABILITY AND CLIMATE

Although we do not know all factors affecting durability, the following climatic parameters determine the lifespan of a material to a large extent:

Solar radiation. Ultraviolet solar radiation deteriorates organic materials by initiating chemical reactions within the material and causing oxidation. This effect is stronger at high altitudes where the ultraviolet radiation is more intense, and it also increases toward the equator.

Temperature. An old rule of thumb is that the speed of a chemical reaction doubles for every 10 °C increase in temperature. Higher temperatures therefore increase the deterioration of organic materials. Emissions of formaldehyde from chipboard containing urea-based glues are doubled with every 7 °C increase of temperature. Heat also stimulates deterioration processes in combination with solar radiation, oxygen and moisture.

At low temperatures, materials such as plastic and rubber freeze and crumble. A porous low-fired brick only lasts a couple of winters in northern Europe – whereas in the Forum in Rome the same brick has lasted 2000 years. Above all the cycle of freezing and thawing is a deciding factor for most porous mineral materials. The coastal climate of the North is also very deleterious. Wide changes in temperature strain materials, even without frost, and will cause deterioration.

Air pressure. Air pressure affects the volume of and tensions within materials that have a closed pore structure, such as foam glass and various plastic insulation materials. Sealed windows will also react. Changes in size that occur have the same effect as temperature changes.

Humidity. Increased humidity can increase deterioration both physically, and by creating an environment for harmful fungus and microbial growth as well as insect attack. Changes of humidity also cause deterioration through changes in volume and stresses within the material. This is why the manufacture of musical instruments such as pianos and violins can only take place in rooms with a very stable air moisture content. The same stable conditions should ideally also be applied to building interiors in order to reduce the deterioration of surface materials and to facilitate cleaning.

Urea-based chipboard, mentioned above, doubles its emissions not only with temperature changes but also with an increase of 30–70% in relative humidity.

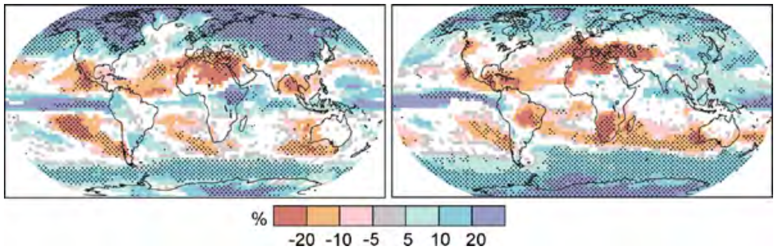
Wind and rainfall. Conditions are at their worst when wind and rain come simultaneously. Then dampness can be driven into the material and start the deterioration process. Strong winds cause pressure on materials that may even lead to fracture or collapse. Wind combined with sand or sea salt can have a devastating effect on certain materials.

Chemicals. Along the coast the salt content of air can corrode plastics, metals and certain minerals. In industrial areas and in the vicinity of heavy traffic, aggressive gases such as sulphur dioxide can break down a variety of different materials. Concrete suffers from so-called 'concrete sickness' where the calcium content is broken down in aggressive environments. This also occurs with certain types of natural stone – as witnessed in the deterioration of many ancient monuments due to modern pollution.

DURABILITY IN THE PERSPECTIVE OF GLOBAL WARMING

Global warming will change materials behaviour significantly. Most regions can expect increased temperatures and in particular, periods of more extreme heat. Many regions are expected to become wetter. This will often occur in combination with increased winds, such as in northern Europe and northern parts of Asia. These regions will also experience more frequent freeze-thaw cycles.

These circumstances will accelerate decay in porous stone, concrete and rendering materials. In Scandinavia an increase in mould growth on organic materials of 50% is anticipated within the next century. Rates of corrosion in metals will increase (Noah's Ark, 2007). On the other hand, in regions such as southern Europe, drier



1.2

Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Scenarios are for December to February (left) and June to August (right), (IPCC, 2007).

conditions may increase damage due to differential thermal expansion and contraction in organic as well as inorganic materials. Migration of destructive insects such as termites may also cause new problems in regions where buildings have never been designed with this in mind.

In some regions climate change may bring decreased risks. In central Europe and the United Kingdom, no great changes are expected in the climatic stresses on building materials. With the exception of the Alpine region, the risks of fungal attack as well as frost damage may, in fact, decrease.

A further factor is likely to be rising water tables, affecting soil chemistry and hence foundation conditions. Rising sea levels and flooding can also cause widespread humidity damage. Here too, future material choices need to be considered for their drying ability and retention of pre-flood properties (Escarameia, 2007).

Building and material decisions thus need to take into account climate scenarios for any particular region. Regional climatic variations are likely to be large; there is therefore a high level of unpredictability in this. As a general rule, however, organic materials need to be given better protection and more robust materials will be needed.

Maximizing recycling

Every material has a resource footprint and a pollution footprint, particularly during production. Much of this can be avoided by recycling products rather than manufacturing from new raw material. A product that can be easily recycled will normally be preferable to a product that is initially quite 'green' but cannot be recycled.

In the building industry many current products and materials have both poor durability and a low recycling potential. There are others that can be recycled several times but in many cases this is seldom done.

Recycling and re-use are more widespread in Holland than in most other industrialized countries. Legislation requires that 80% of demolition materials be recycled into new construction, either buildings or other civil works such as road building. When tendering for contracts, demolition companies have to state how much of the material will be recycled, together with a presentation of how they will do this. There are examples of successful demolition projects where different materials and products have been separated, and a level of up to 95% recycling has been achieved (Holte, 2005). The buildings demolished are often older types with a fairly simple use of materials. For modern buildings, it is doubtful whether the level of recycling can exceed 70%. As a rule, modern buildings also contain larger fractions of problematic, composite or hazardous components that are far more difficult to handle and recycle.

There are also a few examples of successful projects in which whole new buildings have been built composed mainly of recycled materials (Crowther, 2003; Addis, 2006).

However, it is worth remembering that even an ambitious recycling policy is limited by the ratio of new building production to demolition of old ones. At present this ratio is about 4:1 in Western Europe, meaning that recycling can, at most, supply only a quarter of the market for new building materials.

THE DIFFERENT LEVELS OF RECYCLING

Seen from the perspective of industrial ecology, waste can be defined as resources in the wrong place – resources that have gone astray. The goal is to bring all resource flows back into a closed loop where they circulate within the human economic system, so that extraction of new raw materials as well as final discarded waste becomes an absolute minimum (McDonough and Braungart, 2002).

In addition to this principle, there are different levels or degrees of re-use and reprocessing. A range of terms are used to define these levels; however, the three principal ones are (in hierarchical order):

A: Re-use
B: Material recycling
C: Energy recovery

Re-use means the use of a whole component, in largely unchanged form and for a similar function; for example a brick re-used as a brick.

Development of re-usable structures and components has not yet come very far. There are few quality control routines for re-usable products. Efficient re-use of materials or components demands simple or even standardized products. Very few products on the market today meet these requirements. In highly industrialized countries there are as many as 300 000 products in the building industry, all with different designs and composition. At the same time, most buildings are not designed for easy deconstruction. This implies a large risk of damaging the products when buildings are demolished. However, new methods of *design for salvageability* are emerging slowly (Fletcher, 2001; Addis, 2006; Durmisevic, 2006; Nordby et al., 2007).

Historically, re-use of building materials was a normal feature. In many coastal areas old buildings were constructed using a great deal of driftwood and parts of wrecked ships. Nordic log construction is a good example of a building method geared for re-use. The basic principle of mounting robust logs on top of each other, with joints not nails, makes them very easy to take down and re-use, totally or in parts, as well as to move whole buildings to a new site. This building method uses a large amount of material, but the advantages of re-use balance this out.

Material recycling means melting or crushing the component and separating it into its original constituent materials, which then re-enter the manufacturing process as raw material. This is an efficient solution for metals. For other materials, different degrees of *downcycling* lead to products where part of the original value is lost, for example reducing high quality plastic articles to flower pots, or crushing lightweight concrete blocks into aggregate.

The potential for material recycling is also highly dependent upon the purity of the item, since separation of different constituents may be difficult, hence costly or near impossible in the case of quite a few composite building components.

Where products claim to have a potential for material recycling, the statement is often based on theoretical figures. In practice there are often complications: thin aluminium containers often burn up totally or evaporate when being melted; in the worst cases,

1.3

A traditional summer village on the south coast of Turkey. The huts are made of driftwood, packaging and other available free material.

small amounts of impurities in waste products can lead to a need for extra refining processes and a higher use of energy than for new raw materials.

Energy recovery means burning the demolished product to produce energy. Here, all the original raw material resource is lost and only its energy content is recovered. It is therefore a lower grade of recycling. This is, however, clearly a very economical and even profitable way to treat many forms of waste. It is especially advantageous if the materials can be burned at a local energy plant, to reduce transport energy; and if the waste-to-energy products do not contain toxic residues requiring complicated flue gas treatment.

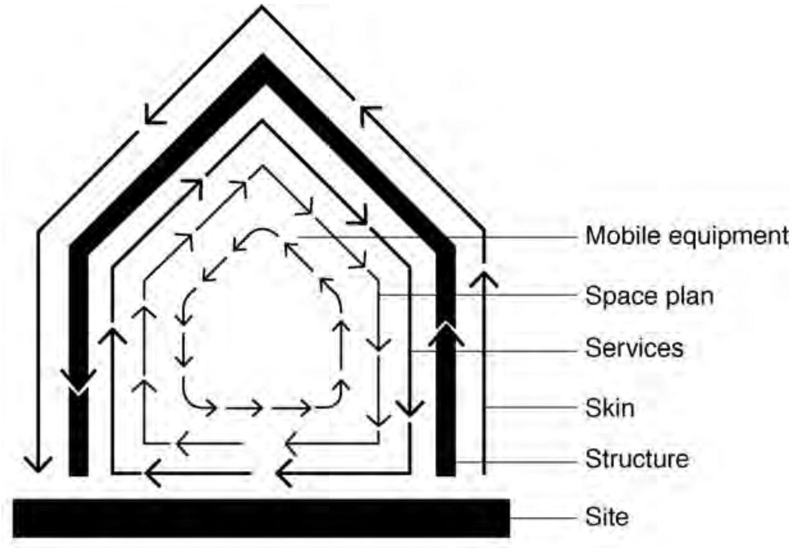
DESIGNING FOR SALVAGEABILITY

An optimal environmental choice is a building with high adaptive capacity, designed for easy maintenance, disassembly and re-use of constructions and components. The following are basic principles.

FIRST PRINCIPLE: SEPARATE LAYERS

A building consists of several parallel layers (systems): interior, space plan, services, structure, skin (cladding) and site (see Figure 1.4). The main structure lasts the lifetime of the building – 50 years in Norway and Britain and closer to 35 in the USA (Duffy, 1990) – while the space plan, services, etc. are renewed at considerably shorter intervals. In modern buildings the different layers are often incorporated in a single structure. Initially this may seem efficient, but the flow in the long-term cycles will then block the short-term cycles, and short-term cycles will demolish slower cycles via constant change. It is, for example, normal to tear down buildings where installations are integrated in the structure and difficult to maintain.

We need a smooth transition between layers, which should be technically separated. They should be accessible independently at any given time. This is a fundamental principle for efficient re-use of both whole buildings and single components.



SHEARING LAYERS OF CHANGE. Because of the different rates of change of its components, a building is always tearing itself apart.

1.4

The main layers of a building.

Source: Brand, 1994.

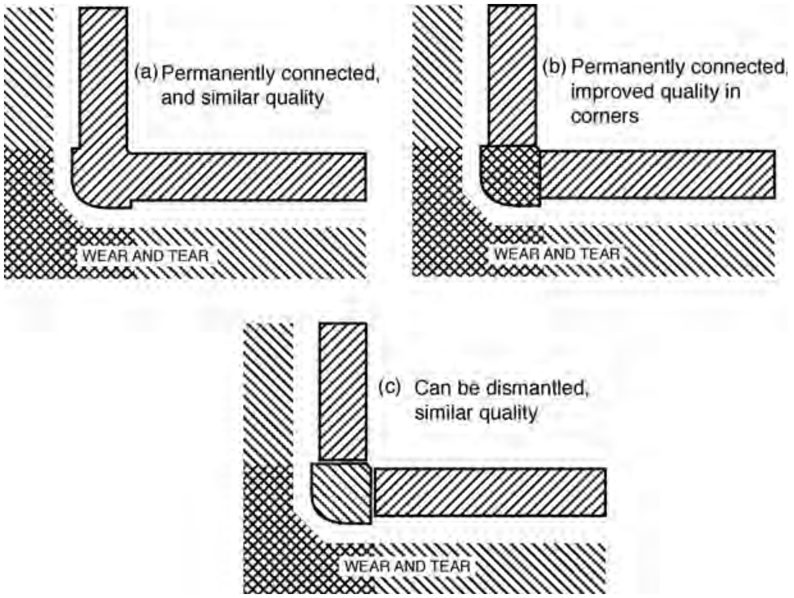
SECOND PRINCIPLE: POSSIBILITIES FOR DISASSEMBLY WITHIN EACH LAYER

Single components within each layer should be easy to disassemble. Figure 1.5 shows three different principles for assembling a wall cladding at a corner. The shading shows where the mechanical wear and tear is greatest, from people, furniture, wind and weather. The normal choice today is the first solution, (a), where all parts are of similar quality and permanently connected. When the corner is worn, the whole structure follows with it. In many expensive public buildings, solution (b) is chosen. By increasing the quality of the most exposed parts, the whole structure will have a longer lifetime. This is usually an expensive solution and makes changes in the space plan difficult. In solution (c), fast wearing parts can easily be replaced separately. The used component can even be re-used in another place where the aesthetics are less important, or it can be sent for material or energy recycling.

THIRD PRINCIPLE: USE OF STANDARDIZED MONOMATERIAL COMPONENTS

Before re-use of the components it is necessary to check their quality. This often presents problems. Many building components are composed of different materials laminated together (see Figure 1.6). Re-use of such products is difficult. Different rates of decay within the same component may result in one of the materials being partially decayed whilst the others are still in good condition. This problem is especially acute in large, prefabricated building elements where cladding, insulation and structure are integrated in a single component.

For re-usable structures only so-called primary and secondary monomaterials should be used. A primary monomaterial is a single homogeneous material used in its natural state, for example untreated wood. A secondary monomaterial is a mixed material of homogeneous nature, e.g. concrete, glass or cellulose fibre. By only using monomaterials it is usually easy to check its quality for re-use. This will be even easier if materials are supplied with an identification code with information on type and application.



1.5

Three constructional concepts for a corner.

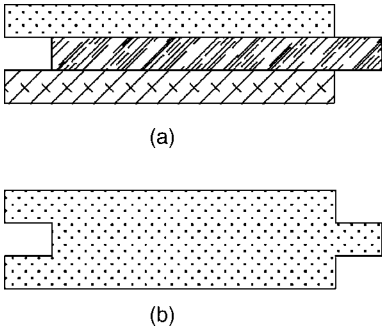
Even if re-use products are thoroughly quality controlled, there still may not be a market for them. The shape of the components may be so unusual that they would need to be transported some distance to find a buyer. So this whole strategy can quickly become an energy problem. Re-usability is therefore also determined by the generality of components.

Most components of buildings could in principle be designed for re-use in this way, though some, such as electrical installations and other technical features, may be inherently less suitable for re-use, in particular since totally new technology may have become current.

At all levels of recycling there will be some waste. Even when full recycling is done, there are still materials left over which need to be taken care of. This can be a large fraction if the material quality is poor to start with, as in the case of waste paper pulp that has already gone through several rounds of recycling. Alternatives in such cases are *dumping* or *global recycling*. Global recycling means composting the materials, or in some other way biodegrading and reintegrating the materials into nature. For example, when cellulose is composted, it is first covered by earth; a series of complex biological processes follow in which mould deteriorates the cellulose structure. Special enzymes in the mould release carbohydrates that stimulate bacterial growth which in turn attacks the molecular structure of the cellulose and releases soluble constituents of nitrogen. The end product is humus, thus becoming a new resource for different plant organisms, providing nutrients for the growth of new cellulose fibres.

In this way global recycling is based almost entirely on closed cycles, which means that there is hardly any waste. These methods can also be considered a more sensible way of depositing a material compared with ordinary material recycling or energy recovery.

Designing buildings almost entirely based on easily biodegradable materials can reduce demolition waste to a minimum (Sassi, 2006).



1.6

(a) Multimaterial component; (b) mono-material component.

However, many biodegradable materials available for building today have some form of additives or chemical treatment.

1.1.3 Raw materials in a world context

Most of today's global *consumption* of materials takes place in the northern temperate zone. But that doesn't mean that most are *produced* in this part of the globe. Throughout modern times most mineral and fossil resources have come from the so-called *developing* countries. This is, however, changing rapidly. Today, 70% of exports from these countries – in particular from Asia – consist of refined or value added products (Achear, 2006).

Although most consumption continues to be in the North, industrialization is accelerating in the South, not least due to considerable relocation of our industries there in order to exploit cheaper labour and energy prices, lower environmental requirements and other advantages. This trend applies in particular to clothing, cars and electronics. For the present this seldom includes building materials, partly because long distance transport of heavy items is costly. There are, however, already exceptions; for example, chemicals used in the plastics industry, such as phosgene which is the base chemical for polyurethane. This could be prohibitively expensive to produce in Europe due to environmental legislation. The same applies to labour-intensive construction materials, such as granite and marble products that today are often cheaper to import from as far away as China.

1.7

Beddington Zero Energy Development (BedZED) in Surrey (UK) with extensive re-use of timber, steel and brick. Building materials were selected from renewable or recycled sources within 35 miles of the site, to minimize the energy required for transportation. Bill Dunster Architects, 2002.

1.2 ENERGY RESOURCES

On current projections, there are sufficient gas and oil resources for another 40 to 60 years. Coal reserves may last for another 150 years at current rates of use. Burning of fossil fuels is the main source of greenhouse gas emissions and the United Nations Climate Panel advises rapid reductions (IPCC, 2007). This implies a need for widespread development of renewable energy sources and/or nuclear power. Nuclear power has a great many risks as well as unresolved waste problems, whilst the renewables are safe but are seen as difficult to harness.

The building industry is a giant amongst energy consumers; its use of energy is divided between the production, operation and demolition phases of buildings, and amounts in total to no less than 40% of all energy used in society. Sustainable construction is thus one of the most important challenges we face. And the potential for improvement is huge.

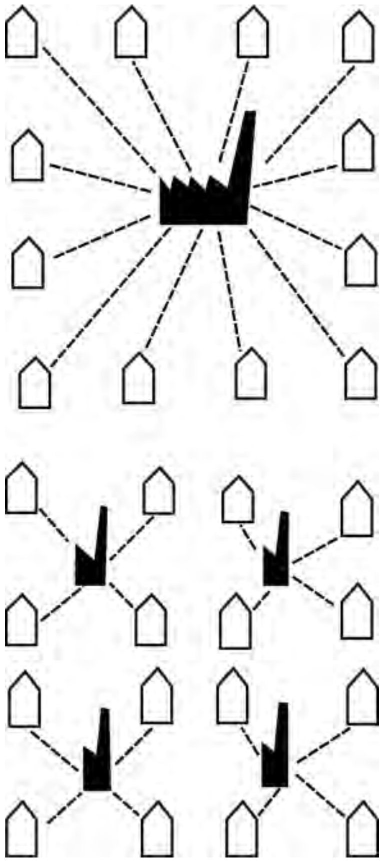
1.2.1 Stages of energy consumption in building materials

The manufacture, maintenance and renewal of the materials in a conventional building over a 50-year period require energy amounting to between 2000 and 6000 MJ/m^2 (Gielen, 1997; Thormark, 2007). The main reason for this very large variation lies in our choice of building materials. For example, timber structures typically require 30% lower energy than concrete ones.

Further, the part of this energy use that is directly dependent on the materials used, normally comprises between 10 and 25% of the total energy use over the whole building lifecycle (Kram, 2001). By far the largest part is therefore needed to operate the building during its lifetime. However, with today's low energy buildings, the lifetime operation takes far less energy and at the same time energy needed to produce the building is increasing. For advanced low energy buildings, this fraction can be as high as 50% of the total lifetime energy used (Nielsen, 1995; Winther, 1998; Thormark, 2007).

This implies that there is an optimum where further increases in insulation thickness and other energy-consuming product inputs into the building itself cannot be justified in terms of the added energy saving that will be achieved in the operational phase.

It is thus becoming clear that the issue of *building materials* is in fact as important as the issue of reducing operational energy use in buildings. This, however, is quite a new perspective and it is not yet being recognized by the majority of today's decision makers.



1.8

Local industries create less need for transport.

EMBODIED ENERGY OF BUILDING MATERIALS

The *embodied energy* of a product includes the energy used to manufacture it all through the process of mining or harvesting the raw materials, refining, processing, and various stages of transport, to the finished product at the factory gate. Other

Table 1.2 *Energy consumption in transport*

Type of transport	*MJ/ton km*
By air	33–36
By road, diesel	0,8–2,2
By rail, diesel	0,6–0,9
By rail, electric	0,2–0,4
By sea	0,3–0,9

inputs include, for example, the energy costs of restoring mined areas, marketing and packaging, even though they may be minor. Also included in the embodied energy is the combustion value of the raw materials themselves, often called feedstock. If incinerated after subsequent demolition the energy content recovered from the product will be given as a negative value and subtracted from the total energy consumed. However, as noted above, the valuable energy content that could be recovered by combustion may be lost due to problematic non-flammable or toxic additives.

The embodied energy of materials is usually about 85 to 95% of the total energy input in the production of a building and is divided up in the following way:

- The direct energy consumption in extraction of raw materials and the production processes, can vary according to the different types of machinery for the manufacturing process.
- Secondary energy consumption in the manufacturing process refers to energy consumption that is invested in the machinery, heating and lighting of the factory and the maintenance of the working environment.
- Energy in transport of the necessary raw and basic materials depending on distance, type of fuel and method of transport.

ENERGY CONSUMPTION FOR ERECTION, MAINTENANCE AND DEMOLITION OF THE BUILDING

The remaining 5 to 15% of the total energy input consists of the construction site, transport and operational processes involved in erection, maintenance and demolition.

- *Energy consumption for the transport of manufactured products* from factory to site can have a large role in the total energy picture. For a time, lightweight concrete elements were exported from Norway to Korea using 3 times more energy for transport than the initial embodied energy. This illustrates the principle that heavy materials should be used locally. See also example with granite from China in Figure 2.3.
- *Energy consumption on the building site*, includes consumption for heating, lighting and machines. The use of human energy varies depending on construction methods but has a small impact on the overall picture. Assuming one person uses 0.36 MJ energy per hour, the erection of an average dwelling would consume 270–540 MJ.

  The amount of energy used on the building site has grown considerably in recent years as a result of increased mechanization. Drying out of buildings with industrial fans – mainly in order to accelerate the building completion time – is relatively new and is responsible for a substantial part of this increase. Traditionally the main structure of the building, with the roof, was completed during the spring, so it could dry during the summer. The moisture content of the different building materials also affects the picture. For example, it takes more than twice as long to dry out a concrete wall as it does a massive timber wall.

- *Energy consumption for maintenance and upgrading.* Sun, frost, wind, damp and normal wear and tear lead to maintenance. At the start, materials are often chemically treated and painted. Surface treatment and repainting must then be done regularly. Then follows the replacement of decayed or defective parts. If the building is not designed adaptively for interior changes this may also lead to large added inputs (Thormark, 2007).
- *Energy consumption of dismantling or removal of materials during demolition.* This may amount to approximately 5% of the overall energy input, but a lot less for constructions that are designed for easy deconstruction.

1.2.2 Reduction of energy consumption in the building industry

Since energy consumption in the building industry is closely connected to the use of materials, reduced materials use is critical; see page 6. For the energy sector, the following are additionally important.

Decentralized production reduces transport and is especially appropriate with local materials. Mobile production units are also an interesting option in many cases.

Use of highly efficient sources of energy. Electricity as an energy source produced in thermal power plants from oil, coal and nuclear power utilizes only 25 to 40% of the energy available. Hydroelectricity can be over 60% – still not extremely efficient. Where possible, it is best to avoid electricity and instead use production methods based on direct heat energy or mechanical energy – rotational power being an example.

Maximum efficiency depends on the relationship between the source of energy and the manufacturing process used. This principle relates to thermodynamics and describes levels of energy quality (see Table 1.3). Where electricity is produced in thermal power plants

Table 1.3 *Energy qualities from renewable sources*

Energy sources	*Energy qualities*					
	Mechanical	*Electricity*	*Heat*			
			Above 600 °C	*200–600 °C*	*100–200 °C*	*Below 100 °C*
Sun	(x)	x	(x)	(x)	x	x
Water/wind/waves	(x)	x	x^1	x^1	x^1	x
Biomass	(x)	(x)	x	x	x	x
Biogas/bioethanol	x	x	x	x	x	x
Geothermal					x	x

Notes: x: commercially available; (x): not commercially available; x^1: via electricity.

it should always be in a cogeneration system producing heat as well as power – but this depends on the industry being located next to other functions that have a need for heat.

The energy needed to keep a worker and her family is so small that it has little effect in the total energy calculation. Labour-intensive processes are almost without exception energy-saving processes.

Use of local sources of energy. The shorter the distance between the power station and the user, the smaller the amount of energy lost in distribution. Over larger distances these losses can be around 10–15%. Small local power stations have shown definite economic advantages over recent years.

Use of energy-efficient production technologies. It is possible to reduce energy consumption in many of today's industrial processes by using efficient heat recovery and improved production techniques. Cement burning in shaft furnaces needs 10 to 40% less energy than traditional rotational furnaces. In the steel industry one can reduce the use of energy by 50% by changing from open blast-furnaces to electric arc furnaces.

Use of low-energy products. Several studies have indicated that the embodied energy in conventional buildings can be reduced by 15 to 20% by choosing low energy products (Thormark, 2007). A comparison of beams for the new airport outside Oslo showed that the total energy consumption in the manufacturing of steel beams is two to three times higher than the manufacturing of glulam beams (Petersen, 2005).

Natural drying out of the building. There is a lot to be gained by choosing quick drying materials – brick rather than concrete, for example – and by letting the building dry out naturally during the summer season.

Use of building techniques that favour recycling. Many building materials have used a great deal of energy during manufacture. This is especially the case with metals, concrete and bricks. By re-using seven bricks one litre of oil is saved. Material recycling metals can save between 40 and 90% compared with extracting from ore. For other materials the savings achieved by material recycling are less; for example, recycling glass wool insulation saves only about 5% energy.

However, the ability to recycle fairly locally is a decisive factor – otherwise transport energy costs quickly change the picture from gains to losses. This once again is a significant argument in favour of simple materials: many advanced industrial materials have to be transported over long distances to special units for recycling. See page 27 for the reading rules for Table 1.4.

Table 1.4 *Effects on resources*

1		*2*	*3a*	*3b*	*4a*	*4b*	*5*
Material		*Weight*	*Material resources*		*Energy resources*		*Water resources*
		[kg/m^3]	*Raw materials, see Table 1.1. R = renewable*	*Reserves, see Table 1.1. [years]*	*Embodied energy [MJ/kg]*	*Combustion value [MJ/kg]*	*Use of water [litres/kg]*
Cast iron	From ore	7200	17–40	95	13	–	
Steel	Recycled	8000	–	–	9	–	
	Galvanized from ore	7500	17–40–39	22	25	–	3400
	Stainless from ore	7800	17–40–8–25	Appr. 25	25	–	3400
Aluminium	From ore	2700	3	141	200	–	29 000
	85% recycled	2700	3	141	45	–	
Copper	From ore	8930	11	31	85	–	15900
Lead	From ore	11300	19	20	22	–	1900
Concrete with Portland cement	Structure, reinforced	2400	20–1	–	1,5	–	170
	Roof tiles	2200	20–1	–	2	–	
	Fibre reinforced slabs	1200	20–1	–	7	–	450
	Terrazzo	2400	20–1	–	1,5	–	
	Mortar & plaster	1900	20–1	–	1	–	170
Areated concrete	Blocks and prefab units	500	20–30–16–3	141	4	–	300
Light aggregate concrete	Blocks and prefab units	750	20–9	–	5	–	190
Lime sandstone		1600	20–30	–	1	–	50
Lime mortar & plaster		1700	20–1	–	1	–	
Calcium silicate sheeting		875	20–30	–	2	–	
Plasterboard		900	16	–	5	–	240

Table 1.4 *(Continued)*

1		*2*	*3a*	*3b*	*4a*	*4b*	*5*
Material		*Weight*	*Material resources*		*Energy resources*		*Water resources*
		[kg/m^3]	*Raw materials, see Table 1.1. R = renewable*	*Reserves, see Table 1.1. [years]*	*Embodied energy [MJ/kg]*	*Combustion value [MJ/kg]*	*Use of water [litres/kg]*
Perlite expanded		80	26	–	7	–	
	With silicone	80	26–42	41	8	–	
Glass		2400	30–28–20	–	12	–	680
	With tinoxide layer	2400	30–28–20–36	22 (1999)	13	–	
Foam glass	Slabs	100–150	30–28–20–40–22	40	30	–	
Mineral wool	Glasswool	15–30	30–33–20–5–42	35	35	(2)	1360
	Rockwool	30–120	34–20–40–42	41	20	(1)	1360
Stone	Structural	2700	34	–	0,5	–	10
	Slates	2700	34	–	0,5	–	10
Earth	Compressed, structural	2000	13	–	0,5	–	
	Loam plaster	1700	13	–	0,5	–	
Fired clay	Well-fired bricks, massive	1900	9	–	3	–	520
	Well-fired brick, perforated	1700	9	–	3	–	
	Roof tiles	1800	9	–	3	–	640
Ceramic tiles		2000	9	–	8	–	400
Expanded clay pellets		450	9	–	3	–	
Bitumen		1000	42	41	50	(40)	
	Sheeting	1300	42–34	41	40	(30)	
Polyethylene (PE)		940	42(41)	41(63)	110	(43)	
Polypropylene (PP)		940	42(41)	41(63)	115	(43)	

Polystyrene, foamed	EPS	10–50	42(41)	41(63)	125	(48)	
	XPS foamed with CO_2	20–65	42(41)	41(63)	130	(48)	
	XPS foamed with HCFC’s	20–62	42(41)	41(63)	133	(49)	
Polyuretane, foamed (PUR)		28–55	42(41)	41(63)	135	(30)	
Polyvinyl chloride (PVC)		1380	42(41)–24	41(63)	85	(20)	
Timber	Untreated, air dried	550	R	–	16,5	16	330
	Untreated, kiln dried	550	R	–	19	16	
	Laminated	550	R–42(41)	41(63)	21	17	
Cork	Untreated porous boards	130	R	–	30	16	25
Wood shavings	Loose fill	80–125	R	–	19	16	
Wood fibre	Loose fill	35–50	R	–	30	16	
	Matting with starch glue	40–55	R	–	32	16	
	Matting glued with polyolefines	40–55	R–41(40)	41(63)	34	(18)	
	Porous boards, wet process	110–350	R	–	40	16	
	Porous boards, dry process	110–350	R–42(41)	41(63)	36	(17)	
	Porous boards with bitumen	110–350	R–42	41	38	(20)	
	Hard boards	600–900	R	–	40	16	2500
Woodwool cement slabs		230–350	R–20	–	28	(8)	
Chipboard		300–900	R–42(41)	41(63)	22	(14)	1000
Plywood		300–1000	R–42(41)	41(63)	25	(16)	
Flax fibre	Matting glued with poyolefin/polyester fibres	20–40	R–42(41)	41(63)	50	(17)	
Linoleum		1200	R–20	–	30	(10)	140

Table 1.4 *(Continued)*

1		*2*	*3a*	*3b*	*4a*	*4b*	*5*
Material		*Weight*	*Material resources*		*Energy resources*		*Water resources*
		[kg/m^3]	*Raw materials, see Table 1.1. R = renewable*	*Reserves, see Table 1.1. [years]*	*Embodied energy [MJ/kg]*	*Combustion value [MJ/kg]*	*Use of water [litres/kg]*
Hemp fibre	Matting glued with polyolefin/polyester	20–40	R–42(41)	41(63)	40	(17)	
Straw bales		80–100	R	–	14,5	14	
Cellulose	Loose fill 100% recycled	20–60	–	–	19	(15)	10
	Matting from fresh fibre, glued with polyolefin/polyester	45	R–42(41)	41(63)	35	(18)	
	Building paper, 98% recycled	1200	R	–	27	17	
	Building paper with bitumen	1150	R–42	41	32	(22)	
Cardboard sheeting	Laminated with polyvinyl acetate	750	R–42(41)	41(63)	28	(17)	
Wool	Matting glued with polyester	18	R–42(41)	41(43)	29	(4)	
Recycled textiles	Matting glued with polyester	25	R–42(41)	41(43)	16	6	

Note: The table is based on many sources, a.o. Kohler et al., 1994; Weibel et al., 1995; Fossdal, 1995; Gielen, 1997; Møtzl et al., 2000; Krogh et al., 2001; Pommer et al., 2001; Thormark, 2001; Nemry et al., 2001; Buschmann, 2003; Jochem et al., 2004; Mühlethaler et al., 2006; Hammond et al., 2006; IBO, 2006.

RESOURCES

RULES OF READING (TABLE 1.4)

The overall scope of the table is Cradle-to-Gate, from the raw materials are harvested until the products are ready to be sent from the factory. Cradle-to-Site can be estimated by supplying with info from *Table 1.2*. Utilization of the combustion value is the hot spot in the rest of the life cycle (Site-to-Grave) and is therefore also mentioned..

Empty squares indicate that adequate information is missing and '–' signify that specification is irrelevant.

AD COLUMNS

Column 1. The choice of additives as fungicides, flame retardants etc is not specified, but still can have a large impact

Column 3. The numbers refer to information given in *Table 1.1*.

Column 4. Embodied energy is defined as the total consumption of energy from the extraction of raw materials until the finished product, including the combustion value of the product itself. It is assumed that waste materials are used as energy sources or as raw materials for other processes and products. The preserved combustion value can eventually be subtracted when the material is incinerated for energy recovery as waste. Brackets indicates that the combustion value is less available due to additional flame retardants and/or substances of toxic character.

Column 5. Describes the amount of water which will have its quality drastically reduced as a result of the production. Recycling or purification of water is not taken into consideration.

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2 Pollution

People in every industrialized country have daily contact with pollution problems: Climate gas emissions are already almost certainly the cause of most extreme weather events. Between 80 and 90% of all cases of cancer are influenced by environmental factors and the prevalence of allergies is rapidly increasing. At the same time, the rate of extinction of animal and plant species is accelerating – between 1900 and 1950 one species each year disappeared, while in 1990 alone, between one and three species disappeared every hour. Species have always died out and new ones have appeared, but the rate of extinction today is 100 to 1000 times greater than the natural rate (Lawton and May, 1995).

The building industry is directly or indirectly responsible for a great deal of humankind's environmental pollution. This can be referred to in terms of *energy pollution* and *material pollution*.

2.1 ENERGY POLLUTION

Energy pollution relates closely to the amount and source of energy used in the production of materials. Transport both of raw materials and finished products is also a decisive factor.

Sources of energy vary a great deal from country to country. In Scandinavia, hydropower is quite common, whereas in Great Britain and Europe the main sources are still fossil fuels and nuclear power. Renewables are increasing only very slowly.

The use of nuclear power implies risks of radioactive emissions, especially in the management of waste. Fossil fuels cause the greatest emissions of climate gases including carbon dioxide (CO_2), acids such as sulphur dioxide (SO_2) and substances forming photochemical oxidation, such as nitrogen oxides (NO_X). Combustion of waste can also cause serious pollution depending on its composition. Bioenergy in its various forms is not unproblematic either. Apart from competition with food supplies, it is normally to be regarded as climate neutral, assuming replantation. The renewable sources such as wind, wave and solar are generally unproblematic but none of them are without some environmental consequences.

Table 2.1 *Energy-related pollution in production processes based on direct use of fossil fuels and mixed domestic waste*
(Source: Naturvårdsverket, Stockholm 2007)

Sources	*CO_2 [g/MJ]*	*SO_2 [g/MJ]*	*NO_x [g/MJ]*
Oil	75	0,18	0,1
Natural gas	55	0	0,04
Coal	91	0,20	0,15
Coke	103	0,36	0,15
Mixed domestic waste	25	0,05	0,09

The figures do not include emissions from extraction and transportation of the fuels, where about 15% should be added. Electricity is usually produced from a combination of sources also including nuclear power, biomass, hydropower etc and the rate of utilization is a lot lower than by direct combustion. The climate impact for electricity produced in the OECD countries is estimated to be 110 g CO_2 per MJ (IEA/OECD, 2007).
(Source: Naturvårdsverket, Stockholm 2007)

Table 2.2 *Pollution from transport*
(Source: NTM Network for Transport and Environment, Sweden 2008)

Type of transport	*CO_2 (g/ton km)*	*SO_2 (g/ton km)*	*NO_x(g/ton km)*
By air	1650	0.9	7.7
By road			
- Light truck (14 tonnes), diesel	175	0.04	1.8
- Heavy truck (40 tonnes), diesel	50	0.03	0.55
By rail, *diesel*	18	0.005	0.36
By sea			
- Small ship (less than 3000 tonnes), diesel	25	0.4	0.7
- Large ship (larger than 8000 tonnes), diesel	15	0.26	0.43

(Source: NTM Network for Transport and Environment, Sweden 2008)

ELECTRICITY AND CLIMATE

Electricity comprises a varying fraction in the energy system of different countries. Clean and convenient at the point of use, it nevertheless usually has huge impacts farther upstream. The source of building materials used may thus be of great importance. Aluminium produced with clean hydropower in Norway has a very small impact compared to aluminium produced with coal-based electricity in England. However, with electricity markets becoming increasingly global, our focus should be on the global energy mix for the production of electricity. This is difficult to ascertain but can be roughly estimated as being produced from the following sources: 66% fossil fuels, 16% atomic power and 18% renewables (Achear, 2006). More detailed information is available for the OECD countries and is used as a basis for the tables of this book. But it is important to remember that the same materials imported from quickly developing countries such as China may have far higher climate impacts related to electricity production.

2.2 MATERIAL POLLUTION

Material pollution relates to pollutants in the air, earth and water stemming from the material itself and from its constituents when being processed, used and during decay. The picture is extremely complex, considering that about 80 000 chemicals are in use in the building industry, and that the number of health-damaging chemicals has quadrupled since 1971. Long-term and not easily reversible damage to groundwater systems and local biotopes also occurs during extraction and mining. Some mines dating back to antiquity still cause serious health and pollution consequences today (Grattan *et al.*, 2003).

Material pollution from construction consists of emissions, dust and radiation from materials that are exposed to chemical or physical activity such as warmth, pressure or damage. Within the completed building these activities are relatively small, yet there is evidence of a number of materials emitting gases or dust which can lead to health problems for the inhabitants or users; primarily allergies, skin and mucous membrane irritations. The electrostatic properties of different materials also play a role in the internal climate of a building. Surfaces that are heavily negatively charged can create an electrostatic charge and attract dust. Electrical conductors such as metals can increase existing magnetic fields. Building materials can also contain radioactive constituents such as radon gas that can be emitted to the indoor air.

Waste is part of the pollution picture though, as waste materials move beyond the scope of everyday activity, it tends to be overlooked. The percentage by weight of environmentally hazardous materials in demolition waste is relatively small, but is still a large quantity and has a considerable negative effect on the environment. Whilst some materials can be burned in an ordinary incinerator, others need incinerators with highly efficient flue gas purifiers. Few incinerators can do this efficiently – many still emit damaging compounds such as SO_2, hydrogen chloride (HCl), heavy metals and dioxins. Depending on the environmental risk, disposal sites must ensure that there is no seepage of the waste into the water system. The most dangerous materials are those containing heavy metals and other poisons, and also plastics that are slow to decompose and cause problems because of their sheer volume.

There is an evident correlation between the natural occurrence of a material and its potential to damage the environment (Table 2.3). If the amount of a substance in an environment (in air, earth, water or organisms) is increased, this increases the risk of negative effects.

2.3 GLOBAL WARMING

Global climate change is probably the greatest threat we face today (IPCC, 2007) (Figure 2.1). A wide range of greenhouse gases must be considered (Table 2.4). Carbon dioxide comprises over half of all greenhouse gas emissions.

The three principal anthropogenic sources of these climate gases are energy production, chemical industry and waste cycles. Of these, the energy related sources dominate. They stem mainly from fossil fuel combustion in power plants and the transport sector.

Table 2.3 *Natural occurrence of the elements in the accessible part of the Earth's crust*
Source Hägg, 1984. See also the Periodic Table in Figure 4.1.

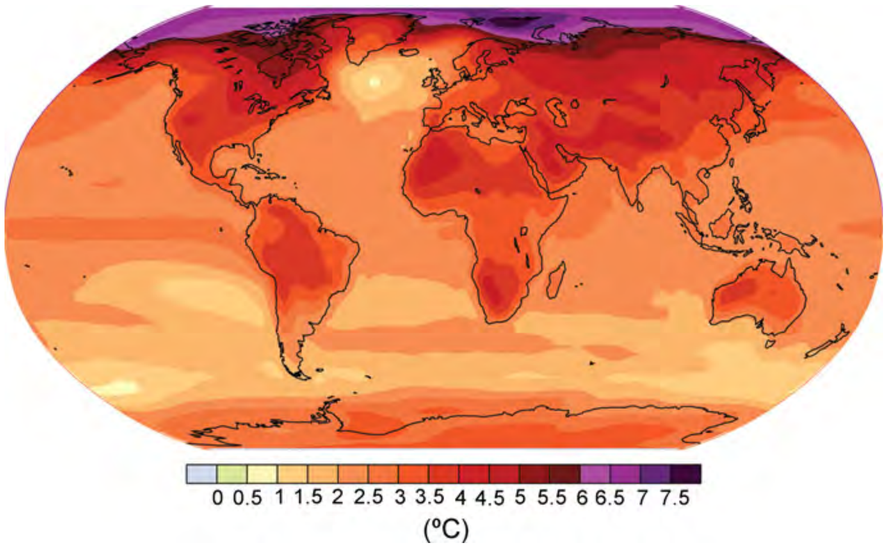
Amount (g/ton)	*Elements*
Greater than 100 000	O, Si
100 000–10 000	Al, Fe, Ca, Na, K, Mg
10 000–1000	H, Ti, P
1000–100	Mn, F, Ba, Sr, S, C, Zr, V, Cl, Cr
100–10	Rb, Ni, Zn, Ce, Cu, Y, La, Nd, Co, Sc, Li, N, Nb, Ga, Pb
10–1	B, Pr, Th, Sm, Gd, Yb, Cs, Dy, Hf, Be, Er, Br, Sn, Ta, As, U,Ge, Mo, W,Eu, Ho
1–0.1	Tb, I, Tm, Lu, Tl, Cd, Sb, Bi, In
0.1–0.01	Hg, Ag, Se, Ru, Pd, Te, Pt
0.01–0.001	Rh, Os, Au, Re, Ir

Source Hägg, 1984. See also the Periodic Table in Figure 4.1.

2.3.1 Climate emissions from the building sector

The construction sector is responsible for a large part of the total global emissions of climate gases. This has been estimated to about 30–40% (United Nations Environment Programme, http://www.unep.org) and relates to operational emissions (heating, lighting, etc) on the one hand, and on the other hand emissions related to production, maintenance and demolition.

Impacts related to the production of materials correspond closely to the embodied energy in the materials (Chapter 1, page 19) though chemical emissions from the products can also play a role. An important example is calcination of lime during cement production, where large amounts of CO_2 are released. Other significant contributions come from volatile organic compounds (VOCs) in the paints industry



2.1

Projected surface temperature changes for the late 21st century (2090–2099). Temperatures are relative to the period 1980–1999 (IPCC, 2007).

Table 2.4 *Important greenhouse gases related to the production, use and waste management of building materials*

Substance	*CAS No*	*GWP [kg CO_2-ekv./kg]*	*Possible occurrence*
Carbon dioxide	124-38-9	1	Processes based on fossil fuels, cement and lime production, waste treatment (incineration)
Chloromethane	74-87-3	16	Plastics, synthetic rubbers, insulation foams
Dichloromethane	75-09-2	15	Paints, insulation foams
Hydrochlorofluorocarbons			Insulation foams
- *HCFC 22*	75-45-6	1700	
- *HCFC 141b*	1717-00-6	630	
- *HCFC 142b*	75-68-3	2000	
Hydrofluorocarbons			Insulation foams
- *HFC 134a*	811-97-2	1300	
- *HFC 152a*	75-37-6	140	
- *HFC 245*	460-58-6	950	
- *HFC 365*	406-58-6	890	
Methane	74-82-8	21	Animal materials (ruminants), steel and cement production (coal mining), waste treatment (landfills, incineration)
Nitrous oxide	10024-97-2	310	Plant materials (artificial fertilizers), waste treatment (incineration)
Pentane	109-66-0	11	Insulation foams
Sulphur hexafluoride	2551-62-4	23900	Double glazing
Perfluorcarbons PFCs			Aluminium production
- *Perfluoromethane*	75-73-0	6500	
- *Perfluoroethane*	76-16-4	9200	

The *Global Warming Potential* (GWP) of a gas is its relative potential contribution to climate change over a 100 year period where *carbon dioxide* $CO_2 = 1$. Emissions of organic solvents used e.g. in paints, adhesives and plastics, will have a GWP of approximately 3 by reacting to CO_2 in the atmosphere. These gases are however not considered as ordinary greenhouse gases and are therefore not mentioned in the table.
Greenhouse gases presented in this table are given a grey colour when they appear in the main text.

and perfluorocarbons (PFCs) from aluminium production. Hydrofluorocarbons (HFCs), often used as foaming agents in insulation materials, are also potent greenhouse gases. These will continue to be emitted throughout the product's lifetime.

In a 50-year lifecycle for conventional buildings, about 10 to 20% of the total greenhouse emissions will be associated with the materials used. However, in the case of low energy buildings, where the heating-related load is less and the materials use is higher, this proportion can exceed 50% (Gielen, 1997). It has been estimated that the production and transport of building materials accounts for 7 to 9% of all climate emissions in Western Europe; the main contributors being steel, cements and plastics (Kram, 2001).

It should be noted that the point in time when these climate emissions are addressed is of great importance. If we wait for 20 years before reducing emissions then the reductions needed will have to be 3 to 7 times more in order to achieve the same effect (Kallbekken and Rive, 2005). This means that material choices are even more important, since their climate emissions mainly occur during the production phase; in other words in the present and immediate future – as compared to reduced heating-related emissions in, say, 40 years' time.

2.3.2 Carbon processes in building materials

During growth, plants absorb and bind large quantities of CO_2 from the air, as well as transferring a quantity to the surrounding soil. Each kilogram of dry plant matter contains about 0.5 kilograms of carbon. This corresponds to sequestration of 1.8 kilograms of CO_2 from the atmosphere. This carbon will remain intact until the material is combusted or decays.

Buildings in timber and other vegetal products, therefore, store carbon for as long as they stand. Assuming that the timber extracted is also being replanted, the overall stock of plant products in the system will be increasing. Carbon storage in building products can thus contribute to reducing the atmospheric CO_2-concentration over a long period and is therefore considered to be a significant contributor to reducing global warming. It 'buys time', since this carbon will not be released back into the atmosphere before the buildings decay in 50 or 100 years' time.

The Kyoto protocol considers reduction options of CO_2 in a 100 year perspective. The lifetime of plant materials storing carbon will thus be critical; if buildings last for only 50 years, their climate effect will be estimated at 50% of that. However, timber constructions can easily have a far longer lifetime – and this can be further increased through more re-use in up to several cycles for some components.

There are other materials that can store carbon. Alkaline earth compounds such as magnesium oxide (MgO) and calcium oxide (CaO) are present in naturally occurring silicate rocks such as serpentine and olivine. When these react with CO_2 they form stable carbonates that can be used both as building blocks and as aggregates in concrete. In theory, there are sufficient of these minerals in the earth's crust to bind all anthropogenic emissions of carbon (Metz, 2006). However, the effects of mining, associated energy use and costs render this an unlikely scenario for the near future.

It should be noted that, whereas the production of cement and other calcium-based building products causes emissions of very large quantities of CO_2 during the calcination of limestone (constituting approximately half of the emissions from the production, the rest resulting from energy use), part of this is later reabsorbed into the materials by *carbonation*. This requires the presence of air and water and takes place over many decades. In the course of a building's lifetime of say 50 years, of the order of 25 to 50% of the carbon originally emitted during calcination may be recaptured. This is significant, but does not greatly reduce the large emission impact of using these materials.

CLIMATE NEUTRAL BUILDINGS

It is possible to construct buildings that are climate neutral throughout their entire life-cycle. This requires that we take into consideration both the materials' aspects as well as operational energy use. Such buildings will have both a climatic 'debit' and 'credit' account, and must be based on the following principles.

FIRST PRINCIPLE: CHOOSE LOW IMPACT MATERIALS AND CONSTRUCTIONS

All materials chosen must have minimal fossil energy demand in production and transportation. Products with chemical emissions of greenhouse gases should be omitted.

Using timber instead of concrete or bricks, for example, reduces emissions from the materials production by approximately 1 kg of CO_2 per kilogram of timber used (Kram, 2001). Even with fairly moderate substitution, one may reduce the climate emissions by some 20 to 30% (Nemry *et al.*, 2001; Pingoud *et al.*, 2003; Thormark, 2007). Over 50% is possible given less conventional materials and solutions (Goverse *et al.*, 2001). This also requires choosing materials that are easy to maintain and to modify and recycle. One should also ensure that the combustion value of biological waste materials is energy-recovered so as to replace fossil fuels. In the case of materials based on fossil resources, in particular plastics, controlled dumping may be the best solution from the climate point of view, since energy recovery from these results in emissions of greenhouse gases corresponding to burning the same amount of fossil fuel.

Use of lightweight materials will reduce transport related emissions. It is estimated that 1 kg of wood can replace 3.6 kg of concrete or brick (Pingoud *et al.*, 2001). On the other hand, the thermal capacity provided by the heavy materials will reduce this advantage somewhat. This depends to a large extent on factors related to construction methods, local climate and building type.

SECOND PRINCIPLE: REDUCE ALL OPERATIONAL ENERGY, IN PARTICULAR THAT BASED ON FOSSIL FUELS

Operational energy includes space-heating, electricity and hot water.

It is important to remember that choice of the best strategies will often depend on very local climatic factors. For example, in windy coastal regions improved air tightness measures will have far more effect than extra insulation.

THIRD PRINCIPLE: MAXIMIZE STORAGE OF CARBON

Use as much construction material as possible that is of plant origin – in practice mainly timber – and in ways that ensure long life as well as reusability (Figure 2.2). Even in Finland, where timber construction is already dominant, it has been estimated that use of timber in construction could well be increased by 70% (Pingoud *et al.*, 2003). A potential of up to 550 kilograms of timber products per square metre of floor area is achievable in small houses. This is based on the use of massive timber constructions in walls, floors and roofs. For larger building types, 300 to 400 kg/m^2 may be realistic (Berge, 2004).

2.4 OTHER POLLUTANTS

2.4.1 Environmental poisons

Environmental toxins pose a growing threat to both humans and ecosystems. There is also a lot of uncertainty as to the effects of even small concentrations. Included in this group are the heavy metals and various

2.2

Kindergarten in Flekkefjord, Norway, constructed in massive wood elements and heated with a small wood burning stove. The building is carbon neutral since the carbon stored in the construction more than compensates for the emissions of greenhouse gases orginating from production, maintenance and energy consumption during a user phase of 50 years. The building can also easily be deconstructed for re-erection elsewhere or re-used as single components. Gaia Lista, 2005.

organic compounds. Many of these substances are now in the food chains, spread by sea or air to the most remote places, and are in the process of becoming concentrated in groundwater all over the world. Climate change is almost sure to increase their dissemination.

The use of hazardous chemicals in the EU increased by 20% during the 1990s and stands now at around 8 kg per capita per day (Azar *et al.*, 2002). The construction industry accounts for a large part of this, especially through additives in plastics, chemical treatment agents and paints (Tables 2.5 and 2.6).

2.4.2 Substances that reduce the ozone layer

Ozone-reducing substances are mainly the chlorinated fluorocarbons (CFCs) and have decreased since the signing of the Montreal Protocol in 1987. In construction, they are mainly used as foaming agents for plastics-based insulation materials. This is one area where substitution has proved to be fairly easy and economical. However, the HFCs that are often used now have also turned out to contribute to global warming and are up to 1300 times more potent than CO_2 (see Table 9.5 in Chapter 9).

2.4.3 Acid substances

Substances that lead to acidification of the natural environment reduce the survival rates of a series of organisms. This group of substances include mainly sulphur dioxide (SO_2) and nitrogen oxides (NO_X) formed through burning fossil fuels and other industrial processes. Also release

Table 2.5 *Important polluting substances in production and/or in finished products*

	Substance	*CAS No*	*R-phrases*[1] *(existing and suggested)*	*Possible occurence*
1	*Acetonitrile*	75-05-8	20/21/22-36	Plastics
2	*Acrolein*	107-02-8	24/25-26-34-50	Plastics
3	*Acrylic acid*	79-10-7	20/21/22-35-50	Plastics, adhesives, paints
4	*Acrylonitrile*	107-13-1	45-23/24/25-37/38-41-43-51/53	Plastics
5	Aliphatic hydrocarbons (group) incl. *Pentane, Ethylene* and *Propylene*			
6	Amines (group), incl. C*yclohexamine* and *Dimethylethanolamine*			
7	*Ammonia*	7664-41-7	23-34-50	Plant products
8	Aromatic hydrocarbons (group) incl. *Benzene, Styrene, Toluene* and *Xylene*			
9	*Arsenic*	–	23/25-50/53	Biocides
10	*Asbestos*	12001-28-4 etc.	45-48/23	Cements, gypsum
11	*Benzene*	71-43-2	45- 46-36/38-48/23/24/25-65	Plastics
12	*Benzo(a)pyrene*	50-32-8	43-45-46-60-61-50/53	Bitumen products (traces)
13	*Benzylbutylphtalate BBP*	85-68-7	61-62-50/53	Plastics
14	*Bisphenol A*	80-05-7	37-41-43-62	Plastics, adhesives, paints
15	*Borax*	1303-43-4	62-63	Mineral wool, biocides
16	*Boric acid*	10043-35-3	62-63	Biocides
17	Brominated hydrocarbons (group) incl. *Hexabromocyclododecane*, *Tetrabromobisphenol A* and *Polybrominated diphenyl ethers*			
18	*Bronopol*	52-51-7	21/22-37/38-41-50	Paints
19	*Butadiene*	106-99-0	45-46	Plastics
20	*Butanol*	71-36-3	22-37/38-41-67	Paints
21	*Cadmium*	–	26-45-48/23/25-50/53-62-63-68	Plastics, paints, biocides
22	*Calcium chloride*	10043-52-4	36	Cements
23	*Carbendazim*	10605-21-7	46-60-61-50/53	Paints, plastics
24	Chlorinated hydrocarbons (group) incl. *Chloroparaffines* and *Dichloroethane*			
25	Chlorofluorocarbons CFC (group), see Table 9.5			
26	*Chloromethane*	74-87-3	48/20-40	Plastics
27	*Chloroparaffins CP*	85535-84-8	40-50/53	Plastics
28	*Chloroprene*	126-99-8	45-20/22-36/37/38-48/20	Plastics, adhesives
29	*Chlorothalonil*	1897-46-6	26-37-40-41-43-50/53	Paints
30	*Chrome*		43-49-50/53	Cements, biocides
31	*Colophony*	8050-09-7	43	Plant products, paints, adhesives, cements
32	*Copper*		50/53	Metal sheeting, biocides
33	*Cyclohexylamine*	108-91-8	21/22-34	Plastics

Table 2.5 *(Continued)*

	Substance	*CAS No*	*R-phrases[1] (existing and suggested)*	*Possible occurence*
34	*Decabromodiphenyl ether*	1163-19-5	40	Flame retarder in plastics
35	*Dibutylphthalate* (DBP)	8474-2	22-50/53-61-62	Paints, adhesives
36	*Dichloroethane*	107-06-2	45-36/37/38	Plastics, paints, varnishes
37	*Dichloromethane*	75-09-2	40	Plastics
38	*Dietylhexylphthalate (DEHP)*	117-81-7	60-61	Plastics, paints
39	*Dimethylethanolamine*	108-01-0	20/21/22-34	Plastics
40	*Endosulfane*	115-29-7	24/25-36-50/53	Biocides
41	*Epichlorohydrin*	106-89-8	23/24/25-34-43-45	Plastics, adhesives, paints, varnishes
42	*Ethyl benzene*	100-41-4	20	Plastics
43	*Ethylene*	74-85-1	67	Plastics, adhesives
44	*Folpet*	133-07-3	20-36-40-43-50	Paints
45	*Formaldehyde*	50-00-0	23/24/25-34-40	Adhesives, cements
46	*Hexabromocyclododecane HBCD*	25637-99-4	43-50-33-26	Plastics
47	*Hexachlorobenzene*	118-74-1	45-48/25-50/53	Biocides
48	*Hexane*	110-54-3	38-48/20-62-65-67-51/53	Plastics
49	*Hydrochloric acid*	7647-01-0	34-37	Plastics
50	Hydrochlorofluorocarbons HCFC (group), see Table 9.3			
51	Hydrofluorocarbons HFC (group), see Table 9.3			
52	*Hydrogen cyanide*	74-90-8	26-50/53	Plastics
53	*Hydrogen fluoride*	7664-39-3	26/2728-35	Plastics, aluminium, glass, brick
54	Isocyanates (group) incl. *Methylene diphenyl diisocyante* and *Toluene diisocyanate*			
55	*Isothiazolinone (Kathon)*	26172-55-4	23/24/25-34-43-50/53	Adhesives, paints
56	*Lead*		61-20/22-33,62-50/53	Mounting, paint
57	*Limonene*	138-86-3 etc	38-43-50/53	Paints
58	*Methylene diphenyl diisocyanate MDI*	101-68-8	20-36/37/38-42/43	Plastics, adhesives, varnishes
59	*Methyl ethyl ketone*	78-93-3	36-66-67	Paints
60	*Methyl metacrylate*	80-62-6	37/38-43	Adhesives, plastics
61	*Methyl isobutyl ketone*	108-10-1	20-36/37-66	Paints
62	*Man made mineral fibres MMMF*		38	Mineral wool
63	*Naphthalene*	91-20-3	22-40-50/53	Biocides
64	*Nickel*	740-02-0	23-40-43-48	Metal alloys
65	*Nonylphenol*	25154-52-3	62-63-22-34-50/53	Paints, varnishes, adhesives, cements

Table 2.5 *(Continued)*

	Substance	*CAS No*	*R-phrases*[1] *(existing and suggested)*	*Possible occurence*
66	*Octabromodiphenyl ether*	32536-52-0	61-62	Plastics
67	*Octamethylcyklotetrasiloxane*	556-67-2	53-62	Plastics
68	Organophosphates (group) incl. *Tris (2-chloroethyl)phosphat* and *Tributyl phosphate*			
69	*Parathion*	56-38-2	24-26/28-48/25-50/53	Biocides
70	*Pentachlorophenol*	87-86-5	24/25-26-36/37/38-50/53-40	Biocides
71	Phthalates (group) incl. *Dibutylphthalat, Dietylhexylphthalate* and *Diisobutyl phthalate*			
72	*Phenol*	108-95-2	23/24/25-34-48/20/21/22-68	Plastics, adhesives
73	*Phosgene*	75-44-5	26-34	Plastics
74	*Pentabromodiphenyl ether*	32534-81-9	48/21/22-50/53-64	Plastics
75	Polycyclic aromatic hydrocarbons PAH's (group) incl. *Benzo(a)pyrene* and *Naphthalene*			
76	Polybrominated diphenyl ethers PBDE's (group) incl. *Decabromodiphenyl ether, Octabromodiphenyl ether* and *Pentabromodiphenyl ether*			
77	*Pyrethrin I & II*	121-21-1 & 121-29-9	20/21/22-50/53	Biocides
78	*Quartz, respirable dust*	14808-60-7	48	Natural stones, cements
79	*Resorcinol*	108-46-3	22-36/38-50	Adhesives
80	Siloxanes (group) incl. *Octamethylcyklotetrasiloxane*			
81	*Styrene*	100-42-5	20-36/38	Plastics
82	*Turpentine*	8006-64-2	20/21/22-36/38-43-51/53-65	Paints, varnishes
83	*Tetrabromobisphenol A TBBPA*	79-94-7	50/53	Plastics
84	*Tetrahydrofuran*	109-99-9	36/37	Plastics
85	*Thallium*	–	26/28-33-53	Metals, cements
86	*Toluene*	108-88-3	38-48/20-63-65-67	Paints
87	*Toluene diisocyanate TDI*	86-91-9	26-36/37/38-40-42/43- 52/53	Plastics, adhesives, varnishes
88	*Tributyl phosphate TBP*	126-73-8	22-38-40	Paints, adhesives, cements
89	*Tributyltin oxide*	56-35-9	25-48/23/25-21-36/38-50-53	Biocides
90	*Triethanolamine*	102-71-6	36-37-38	Cements
91	*Tris (2-chloroethyl)phosphat*	115-96-8	20-40-51/53	Plastics, adhesives
92	*Vinyl chloride*	75-01-4	45	Plastics
93	*Xylene*	106-42-3	20/31-38	Plastics, paints, varnishes
94	*Zinc*	–	50-53	Biocides, metal products
95	*Zirconium*	–	38-41-51/53	Paints

For interpretation of R-phrases, see Table 2.6. Compounds listed in this table are given a grey colour when they appear in the main text.

[1] Note that toxic effect depend on dose. Particular substances can also boost the effect of others. Source: (Norwegian Pollution Control Authority, 2008.)

Table 2.6 *Chemical risks to human health and the environment described in R-phrases, (EU Directive 67/548/EEC)*

Classification	*R-phrases*
Carcinogenic effects, known or suspected	40-45-49
Mutagenic effects, known or suspected	46
Effects on reproduction, known or suspected	60-61-62-63-64
Very toxic	26-27-28
Serious irreversible and cumulative effects, known or suspected	33-39-48-68
Allergenic	42-43
Harmful/toxic by inhalation	20-23
Harmful/toxic if swallowed	22-25
Harmful/toxic in contact with skin and eyes	21-24-34-35-41
Irritating to eyes	36
Irritating to respiratory system	37
Irritating to skin	38-66
Repeated exposure may cause drowsiness and dizziness	67
Very toxic/toxic/harmful to aquatic organisms	51-52-53
Toxic to flora, fauna, soil organisms and bees	54-55-56-57
May cause long-term adverse effects in the environment	58
Dangerous for the ozone layer	59

Risks can also be expressed in combined phrases where the individual phrases are connected with slashes, e.g. for Tetrahydrofuran.

of hydrogen chloride (HCl) from combustion of plastic waste leads to acidification. In England it is estimated that 8% of sulphuric emissions come from production and transport of building materials (Howard, 2000).

2.4.4 Formation of photochemical oxidants (low ozone)

Photochemical oxidants are generally very corrosive and usually appear in the form of smog. They are formed when a mixture of nitrogen oxides (NO_X), dust and volatile organic compounds (VOCs) are subjected to sunlight. Within the construction sector, the main source is combustion of fossil fuels. This includes both energy intensive production processes, and transport related emissions both at the raw materials stage and the transport of finished products. The global warming potential (GWP) of building materials is thus also assumed to provide a very good indication of their role in the formation of photochemical oxidants (Statens Forurensningstilsyn, 2002).

2.4.5 Eutrophicating substances

Excessive fertilization and the resulting overgrowth of weeds caused by eutrophicating substances in water systems are known as *chemical oxygen depletion*. Artificial fertilizers used in the cultivation of plants contain phosphorous compounds that are regarded as highly eutrophicating. Suspended organic matter in runoff water from industry can also lead to eutrophication. The main source from the building industry is NO_X stemming from combustion of fossil fuels. The GWP of a material will thus be a good indicator for eutrophication (Strand, 2003).

2.4.6 Particles

Dust and particulates are produced during the extraction of many materials, various industrial processes, on building sites, as well as through incomplete combustion of solid fuel and oil. Dust can be chemically neutral but can also contain environmental toxins.

Polluting particles can also be a problem during the demolition phase. Organic chemistry produces a wide range of synthetic compounds that are difficult to degrade in the environment. Here the largest volumes come from the plastics industry. More and more plastics are used in buildings. These are ultimately broken down into persistent particles. In parts of the Pacific, there are now six times as much of these small plastic particles as plankton. A baleen whale will thus ingest more plastic than plankton. Plastic has been shown to be present in food chains in the Antarctic (Browne *et al.*, 2007). The effects of this are not known, but in addition to the risk of stomach blockage in certain species, many plastics contain toxic additives including heavy metal-based fungicides and bromated flame retardants that can be absorbed and concentrated in most living organisms.

2.4.7 Genetic pollution

Genetically manipulated plant species are now being widely introduced into agriculture and forestry in an effort to increase production and improve resistance to things like cold, mould and insects. The goals are often environmentally legitimate; for example, to reduce the use of pesticides. But it must still be regarded as hazardous. Generally, any change that occurs in a natural species that gives them a defensive advantage also affects that species' environment, and might lead to the extinction of other species. Ingesting of genetically modified food has also been shown to cause changes in the blood and kidneys in tests on rodents (Achear, 2006).

2.4.8 Nanoparticles

Nanotechnology involves synthetic structures of a size less than 100 nanometres (1 nanometre = 10^{-9} metre). One goal is to develop lighter materials and active materials with special properties, including those for use in the building industry. For example, self-cleaning materials coated with a thin film of nanoparticles such as windows have already been available on the market for several years. Similar products are being developed for treating concrete, and applications are likely to increase rapidly. Contamination of ecosystems with nanoparticles has been shown to involve a range of possible risks both for humans and the environment (Meili, 2007). Brain damage in fish, reduced germination in crops, heart and respiratory diseases in humans, are among the suspected effects.

INDOOR POLLUTION

Building materials are the source of various kinds of pollution inside completed buildings.

Many organic materials, as well as mineral materials with organic additives, are apt to host fungal growth when exposed to continuous humidity. These can emit mycotoxins and other serious irritants.

A wide range of common building materials emit particles and gases that carry a variety of health risks. Examples are volatile organic compounds such as solvents in paints. In such cases, emissions will be greatest during the first weeks or months. In other cases, the emissions are persistent, as from plasticizers in soft plastic flooring. In yet other cases, emissions may increase later as a material ages or is exposed to excessive temperature or humidity.

These emissions are most often the cause of respiratory problems, whilst many may increase susceptibility to asthma and allergies, and in some cases they include highly toxic and carcinogenic substances.

Electromagnetic radiation includes both radioactivity and low frequency radiation, and both can affect biological processes. Some materials emit small doses of radioactive radon gas. Materials that are good conductors can increase the low intensity magnetic fields in buildings. Whilst radioactivity is carcinogenic, low frequency radiation is thought by many to be able to cause illness and fatigue.

2.5 REDUCTION OF POLLUTION IN THE PRODUCTION OF MATERIALS

Naturally, pollution from the building industry depends on the amount of resources used. Reductions are therefore a primary strategy – see *Actions for resource conservation in the production of materials* on page 6, Chapter 1 and *Reduction of energy consumption in the building*

Table 2.7 *Energy sources and pollution*[1]

Energy source	*CO_2*	*CO*	*NO_x*	*SO_2*	*Heavy metals*	*Dust*	*Aromatic hydrocarbons*	*Radioactivity*
Sun								
Water/wind/waves								
Geothermal								
Biomass burning	(x)[2]	x				x	(x)[3]	
Biogas/bioethanol burning	(x)[2]	x					(x)[3]	
Natural gas burning	x	x	x				x	
Oil burning	x	x	x	x	x	x	x	
Coal burning	x	x	x	x	x	x	x	
Nuclear power								x

[1] Emissions orginating from the transportation of fuels and the construction of the generation plants are not included.

[2] Considered neutral since emissions are equal to initial uptake through photosynthesis.

[3] Small amounts by effective combustion.

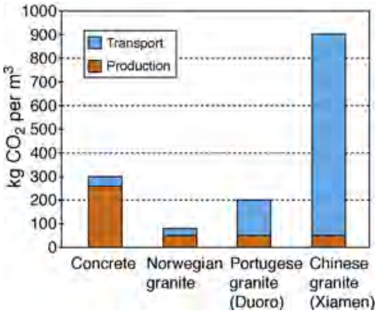
industry on page 21, Chapter 1. In addition, the following are important.

Substitution to non-fossil energy sources for extraction of raw materials and production processes. The possibilities of using renewable energy sources such as solar, wind, hydropower and biomass should be investigated, and priority given to manufacturing processes and materials which put these principles into practice.

Reduced use of toxic chemicals. Preference to materials that are not based on hazardous ingredients or additives.

Careful utilization of natural resources. An increased use of materials that involve less environmentally-damaging methods of extraction and production would entail an increased use of renewable resources and recycled materials.

Efficient purification of industrial processes. There are plenty of possibilities in this area. It is even possible, in some cases, to reprocess waste for the manufacture of new products (see Chapter 12).



2.3

Climate impacts of paving slabs made in concrete and in granite, for use in Norway. The production of granite slabs has much less impact than the production of concrete slabs. But when importing granite from China the emissions of carbon dioxide from transport will quickly offset this advantage. Today China is the dominating producer of granite slabs for the European market (Berge, 2005).

2.6 REDUCTION OF POLLUTION IN CONSTRUCTION, USE AND DEMOLITION

The pollution created in construction, use and demolition of buildings is closely connected to the amount of resources used, e.g. the size of the house, see *Reduction of the use of materials in the building* on page 8, Chapter 1, and *Reduction of energy consumption in the building industry* on page 21, Chapter 1. In addition, the following are important:

Reduced use of products that are responsible for larger emissions of greenhouse gases and other pollutants during production. There is a large potential in switching to materials with less environmental impact. This will often mean choosing materials based on biological resources.

Reduced use of products that emit harmful gases, dust or radiation. Alternative materials are available.

Avoiding organic materials in moist situations. Hazardous substances can be emitted while decaying as well as mould being formed which can emit mycotoxins and other indoor irritants.

Increased use of timber and other biotic resources in long-term products. Products made from plants function as storage of carbon and should be chosen where possible.

See page 47 for the reading rules of Table 2.8.

Table 2.8 *Effects of pollution*

1		*2a*	*2b*	*2c*	*3*	*4*	*5*
Material		*Global warming potential GWP*			*Acidification potential AP*	*Poisons and ozone depleting substances*	*Waste category*
		Basic impact	*Negative modifyers*	*Positive modifyers*		*[See Table 2.5]*	
		[g CO_2 -equ./kg]	*[g CO_2 /kg]*	*[gCO_2/kg]*	*[g SO_2-equ/kg]*		
Cast iron	From ore	750	–	–	6	53-52-12-94	D
Steel	Recycled	1000	–	–	3	94-30-21-9-53	D
	Galvanized from ore	2200	–	–	10	5-8-94-30-21-53	D
	Stainless from ore	2200	–	–	10	5-8-30-21-64-53	D
Aluminium	From ore	15000	–	–	>60	12-53	D
	85% recycled	3100	–	–		12-53	D
Copper	From ore	6000	–	–	140	32-9-85	C
Lead	From ore	1130	–	–	10	56-85	E
Concrete with Portland cement	Structure, reinforced	180	–20	–	0.6	78-30-85	C
	Roof tiles	180	–40	–	0.6	78-30-85	C
	Fibre reinforced slabs	400	–80	–	2	78-30-85	C
	Terrazzo	120	–40	–		78-30-85	C
	Mortar and plaster	200	–40	–	0.8	78-30-85	C
Areated concrete	Blocks and prefab units	270	–20	–	1.2	78-30-85	C
Light aggregate concrete	Blocks and prefab units	330	–20	–	2.3	78-30-85-53	C
Lime sandstone		150	–5	–	0.7	78	C
Lime mortar and plaster		190	–120	–	0.2	–	C
Calcium silicate sheeting		140	–5	–	1	78	C
Plasterboard		250	–	–	2	6	D
Perlite expanded		500	–	–	2	–	C
	With silicone	500	–	+10	2.3	80-6-23-26	D
Glass		700	–	–	44	53-9	C

	With tinoxide layer	700	–	–		53-9-89	D
Foam glass	Slabs	1250	–	–	8	–	C
Mineral wool	Glasswool	1700	–	+100	9	62-72-45-15-78	D
	Rockwool	1740	–	+50	10	62-72-45-52	D
Stone	Structural	10	–	–	0	78	C
	Slates	15	–	–	0	78	C
Earth	Compressed, structural	20	–	–	0.1	–	C
	Loam plaster	20	–	–	0.1	–	C
Fired clay	Well-fired bricks, massive	190	–	–	1	53-78	C
	Well-fired bricks, perforated	190	–	–	1	53-78	C
	Roof tiles	190	–	–	1	53-78	C
Ceramic tiles		570	–	–		53-78	C
Expanded clay pellets		350	–	–	2.5	53-78	C
Bitumen		400	–	+3000	4	12	B/D
	Sheeting	430	–	+2000	4	12	B/D
Polyethylene (PE)		1600	–	+3200	9	43-72-6	B/D
Polypropylene (PP)		1650	–	+3200	7	72-6	B/D
Polystyrene, foamed	EPS	3500	–	+3550	27	81-72-6-17-11-46	B/D
	XPS foamed with CO_2	3700	–	+3550	25	81-72-6-17-11-46	B/D
	XPS foamed with HCFC's	21500	–	+3550	29	81-50-72-6-17-11-46	B/D
Polyurethane, foamed (PUR)		14500	–	+2200	55	54-73-72-50-24-17-37-39-2-45-89	B/D
Polyvinyl chloride (PVC)		3000	–	+1450	13	92-71-27-36-8-5-49-14-21	D
Timber	Untreated, air dried	300	–850	–	0.5	–	A/D
	Untreated, kiln dried	550	–850	–	0.8	–	A/D
	Laminated	700	–825	+50	3	45-72-79	B/D
Cork	Untreated porous boards	600	–825	–	3	–	A/D
Wood shavings	Loose fill	300	–825	–	2	–	A/D
Wood fibre	Loose fill	600	–825	–		15	A/D
	Matting with starch glue	1000	–825	–		–	A/D
	Matting glued with polyolefines	1000	–775	+300		43	B/D

Table 2.8 *(Continued)*

1		*2a*	*2b*	*2c*	*3*	*4*	*5*
Material		*Global warming potential GWP*			*Acidification potential AP*	*Poisons and ozone depleting substances*	*Waste category*
		Basic impact	*Negative modifyers*	*Positive modifyers*		*[See Table 2.5]*	
		[g CO_2 -equ./kg]	*[g CO_2 /kg]*	*[gCO_2/kg]*	*[g SO_2-equ/kg]*		
	Porous boards, wet process	1600	−825	–	9	–	A/D
	Porous boards, dry process	1300	−775	+90	4	54-73-6	B/D
	Porous boards with bitumen	1400	−775	+300	10	12	B/D
	Hard boards	1500	−825	–	5	72-31	A/D
Woodwool cement slabs		1600	−400	–	5	78-30-85	D
Chipboard		700	−775	+200	2.5	72-45	B/D
Plywood		750	−825	+100	0.5	72-45	B/D
Flax fibre	Matting glued with polyolefin/ polyester fibres	1650	−700	+450	11	15-43	B/D
Linoleum		1020	−400	–	1.5	94	B/D
Hemp fibre	Matting glued with polyolefin/polyester	1400	−775	+300	13	43	B/D
Straw bales		5	−800	–		–	A/D
Cellulose	Loose fill 100% recycled	230	−800	–	2.2	45	D
	Matting from fresh fibre, glued with polyolefin/polyester	1600	−775	+300	12	43	B/D
	Building paper, 98% recycled	300	−825	–	0.3	–	A/D
	Building paper with bitumen	320	−750	+600		12	B/D
Cardboard sheeting	Laminated with polyvinyl acetate	400	−775	+100		–	B/D
Wool	Matting glued with polyester	500		+300	5.5	43-15-77	B/D
Recycled textiles	Matting glued with polyester	1320	−325	+300	3	43	B/D

Note: The table is compiled and based on many sources, a.o. Kohler et al., 1994; Weibel et al., 1995; Fossdal, 1995; Gielen, 1997; Mötzl et al., 2000; Krogh et al., 2001; Pommer et al., 2001; Thormark, 2001; Nemry, 2001; Fossdal, 2003; Buschmann, 2003; Jochem et al., 2004; IBO, 2006; Mühlethaler et al., 2006; Hammond et al., 2006; Schmidt, 2006.

POLLUTION

RULES OF READING (TABLE 2.8)

The overall scope of the table is Cradle-to-Gate. The raw materials are harvested until the products are ready to be sent from the factory. Cradle-to-site can be estimated by combining with info from Table 2.2. The tables are also supplied with hot spots from Site-to-Grave and will therefore give a rough picture of the total impact through the life cycle of products.

Empty squares indicate that adequate information is missing and '–' signify that specification is irrelevant.

AD COLUMNS

Column 1. Based on the most common product compositions. Alternative glues and additives can change the picture substantially.

Column 2a. Based on conventional production with fossil fuels and electricity from the municipal grid in OECD-countries. In certain trades, such as the timber industry, the use of biomass for energy production is substantial. This is not reflected in the estimates.

Column 2b. Quantifies the effect of storing carbon in vegetable products and the effect of carbonatation in products based on calcined lime during a period of 50 years see pages 32-34. The latter is estimated to 25% (of the initial chemical emissions from the calcinations processes) in concrete constructions, 50% in sheet products and plasters with Portland cement and 80% in sheet products and plasters with lime.

Column 2c. Quantifies the additional effect of the final waste incineration of products based on fossil raw materials.

Column 4. Indicates hazardous substances that can be found in production and/or in the finished product. Particular brands can be less polluting. The numbers are referring to the first column in Table 2.5.

Column 5. Waste categories:

A. Incineration without purification/composting
B. Incineration with purification
C. Landfill
D. Ordinary tip
E. Special tip
F. Strictly controlled tip

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3 Local production and the human ecological aspect

The concept of sustainable development requires us to consider not only the quantifiable aspects of products, but equally the economic and social ones. Although the social and ethical aspects of building materials are not the focus of this book, it is important to consider the connections involved; for each building component has, in addition to its physical or ecological properties, a 'footprint' relating to what kind of social system, worker environment and community it has required.

Basically there are three different ways of manufacturing a product:

- It can be manufactured by the general user, based on personal needs and skills and usually in accordance with local cultural tradition.
- It can be manufactured by a craftsman who has developed a method of manufacture through experience.
- It can be manufactured through a production engineer who directly or indirectly, including through electronics, informs the worker or machinery of the steps to take.

The first two methods share a common factor: the spirit of the product and the hand that produces it belong to the same person.

Until the early Egyptian dynasties of around 3000 BC, the dominant form of all manufacture was home production. Most people knew how a good hunting weapon should be made, or how to make a roof watertight. Certain people were more adept and inventive than others, but they shared their experience. Knowledge was transferred through generations and became part of the cultural heritage. In most countries, especially in rural communities, home production was the dominant form of manufacture until relatively recently; and this is still the case in many of the so-called developing nations.

Craftsmen have existed for at least 5000 years. During the Middle Ages, guilds were formed; apprentices learned from their masters and further developed their own knowledge and experience. In this way they became masters in their own trade. The working situation of a quarry worker was such that all his senses took part in his work. The quality of the stone was decided by how 'it stuck to the tongue', the resonance of it when struck, the creaking when pressure was applied, the smell when it was scraped or breathed on, or the colour of the stone and the lustre given by scraping it with a knife or nail. The potter, lacking advanced measuring instruments relied on personal judgement to know when the pottery had reached the right temperature in the kiln. This judgement consisted of a potter's own experience of the colour, smell and consistency of the material. As long as the products satisfied customers, the potter could decide how the product was manufactured. The method of production was not split into different parts; the craftsman knew and followed the product through the whole process.

This kind of manufacture, where manual labour was the main resource, continued well into the industrial revolution. In the American steel industry of the nineteenth century, the workers themselves controlled production. They made decisions, led the work and were responsible for engaging new workers. In 1889 this principle became a contractual agreement between workers and their employers, giving them control of all the different parts of production. As we know, this changed. The factory owner Cyrus McCormick II came up with the idea that if he invested in machinery he would be able 'to weed out the bad elements among the men' (Winner, 1986) – that is, the active trade union members. He took on a large number of engineers and invested in machinery, which he manned with non-union men. As a result, production went down and the machines became obsolete after three years. However, by this time, McCormick had achieved what he set out to achieve: the destruction of the unions. Together with the engineers he took full control of production.

People like McCormick introduced the third form of manufacture, which is today the established norm, controlled by the engineer. From the beginning, the engineer has been on the side of the capitalist. In this way, the worker lost control of the manufacturing process; experience and sensitivity were replaced by machinery, instruments and automation.

After the restructuring of the steel industry, many industries in the newly industrialized world followed suit. The car industry switched to engineer-dominated production within just two years. The paint and paper industries followed. In certain other areas, expert-controlled production came somewhat later. The largest bakeries were already under expert control during the 1930s, whereas the timber and brick industries were not broadly controlled by engineers until after the Second World War.

The traditional use of timber as a jointing material disappeared during this period, partly because of new standardization regulations. They were replaced by steel jointing materials, bolts and nails. Whereas steel components of a certain dimension always have the same properties, the properties of timber joints are complex and often verified through experience rather than calculation.

Does it matter which method of manufacture a product undergoes? Adam Smith, one of capitalism's first ideologists, states in his book from the beginning of the industrial revolution, *The Wealth of Nations* (1876):

> A man is moulded by the work he does. If one gives him mundane work to do, he becomes a mundane person. But to be reduced to a totally mundane worker is the destiny of the great majority in all progressive societies.

By *work* is understood the activities intended to fulfil our needs – and most of our life is filled with different kinds of work. In many situations today, specialization and professionalization have transformed work from self-development to mere ‘doing’. However, most will agree that work is not just a means to an end, but an important activity of the community and of the human spirit: a process of self-realization, learning, communicating, and discovery where one learns more about the material one is working with, about oneself and about the world.

3.1 THE QUALITY OF WORK

The relationship between producer and consumer in worker-controlled production is called a ‘primary relationship’. Engineer-controlled production is a ‘secondary relationship’. In the latter case, contact between consumer and producer seldom occurs; at the most, the consumer is only aware of the country in which the last process of production took place. The name of the company often gives very few clues. However, in the primary relationship the consumer and the manufacturer often have a close relationship with each other.

ASPECTS OF THE PRIMARY RELATIONSHIP

The primary relationship has positive effects for both the consumer and the manufacturer.

FOR THE CONSUMER:

Better product

It is quite normal today to have built-in weaknesses in products manufactured by engineer-controlled methods in order to increase sales. There are also examples in the USA where frustrated production line workers have taken secret revenge by compromising the quality of cars and other products that have rolled past them.

It is doubtful that a skilled worker in a primary relationship would make a product with reduced durability on purpose, partly because of professional pride and partly for fear of being reprimanded directly. In this way there is a guarantee in the primary relationship.

Responsible use of resources and less pollution

It is doubtful that a small industry manufacturing products for the local community would bury barrels of toxic waste in the area. A small industry, based on local resources, would most likely have a much longer perspective in planning the use of resources than a larger firm with a widespread base.

FOR THE MANUFACTURER:

Safer places of work

Worker-controlled industries limit their own size and will remain local. People living in such an area realize that, by buying local products, they are supporting the local industries; and that everyone is dependent upon everyone else. People are also aware of any unemployment – this can, in turn, create a basis for solidarity.

Meaningful work

There is a big difference in the scope and challenge of the work for a carpenter who builds a complete house, and a carpenter who just fits windows in to a prefabricated house. The latter misses two important aspects of their identity as a builder:

a relationship with the completed house and with the client. Instead, this carpenter only forms a relationship to many houses and many clients, which is abstract. While, in the former case, close contact between the carpenter and client increases the possibility of a far more personal touch in the product.

FOR THE MANUFACTURER AND THE CONSUMER:

Less bureaucracy

In most cases there is a feeling of solidarity in the primary relationship. In the secondary relationship solidarity is replaced by laws, rules, production standards, etc. and expensive and inefficient bureaucracy. So-called extended producer responsibility is strongly favoured today as the basis for more sustainable industry. It is important to note that this is an issue of looking at production structures themselves, rather than ever new ways of regulating; for example, stricter environmental standards. Such industry is intended to focus more on longlife products as well as ecological responsibility in general. This kind of solution has shown itself to be far more difficult to implement in productions based on the secondary relationship.

Flexibility

Possibilities for spontaneity and improvisation in the production process, e.g. to change a door handle or restyle a suit, are much greater in the primary relationship. This has to do with the use of imagination, which we can assume is appreciated by both the manufacturer and the consumer.

The philosopher E. F. Schumacher sums it up like this: ‘What one does for oneself and for friends will always be more important than what one does for strangers’ (McRobie, 1981).

With the continual division of industry into separate skills there has also been an increasing geographical division of work – a specialization of space – with whole communities themselves being shaped around specialized industries. There are communities whose inhabitants work entirely for one aluminium factory, for example. Opportunities for different experiences become less and less since the essential qualities of variation and complexity in the community are strongly reduced (Kvaløy, 1973). As with the division of work, the geographical division of specific skills or industrial processes inevitably has socio-political aspects. A community of specialized workers can easily become the victims of administrative decisions contrary to their own local interests.

3.2 TECHNOLOGY

Schumacher opposes any form of technology that takes away from people the joy of creating. He states that work fulfils at least three different functions: to give every person the possibility to use and develop their skills; to encourage people to overcome egoism by doing things together; and to produce articles that are not superfluous but necessary for everyday life.

Ivan Illich focuses even more on the role of power: ‘We must develop and use tools that guarantee man’s right to work efficiently without being controlled by others, and thus eliminate the need for slaves and masters’ (Illich, 1978).

There is a tendency to regard technology as neutral and to believe that political aspects only come into play when technology implemented. A knife can illustrate this view: it can be used to cut bread or to kill someone. But when an industrial robot becomes part of a workforce, it is obvious that it not only increases productivity but also redefines the whole nature and qualitative conditions of work at that production site.

From the history of the building industry we have seen how small changes in the use of materials can have far-reaching consequences. Until about 1930 nearly all mortar used was lime mortar. Bricks could, therefore, only be laid in meter high shifts since the mortar needed time to harden. The bricklayers had to take a break and often used that time to design or do other detailed work. Then, with the introduction of Portland cement, this changed the situation drastically. Within a few years, architects and engineers took over the task of detail design, which had been the mason's job for centuries.

Most of today's technological structures still place efficiency and profit before a human's qualities in work. Real, long-term service value to the consumer is seldom the result, and the environment has often suffered. The technology philosopher Langdon Winner maintains that 'much could have been left undone'. His colleague Jonas follows with the statement: 'One shall only do a part of everything one is actually capable of doing'. Today's society is ruled by a high degree of technological determinism. It is taken for granted that the technological development has its own momentum, which cannot be hindered in any way.

As early as in the 1960s, Lewis Mumford stated: 'From late Neolithic times in the Near East, right down to our own day, two technologies have recurrently existed side by side: one authoritarian, the other democratic, the first system-centred, immensely powerful, but inherently unstable, the other man-centred, relatively weak, but resourceful and durable' (Mumford, 1964).

Thus there is an issue of more or less *democratic* building materials. On the one hand products with a low degree of technology and processing, such as clay, natural fibres and timber, and on the other, highly industrialized products such as aluminium and plastics. The industrial ecologist Hardin Tibbs wrote about the potential of combining benign materials with eco-networking. The key, he said, 'would be first to identify a set of materials which have a long-term geophysiological compatibility. A fairly small set of acceptable materials could probably be used to supply 80% or more of all production needs. The next step would be to devise clusters of production processes that use some or all these materials, and which can be interlocked ecosystem-style. Once this was done, the resulting industrial clusters or industrial ecosystems might stand a reasonable chance of being stable over time' (Tibbs, 1998).

3.3 ECONOMY AND EFFICIENCY

Principles for an ecological building industry include the following:

- The technological realm should be moved closer to both the worker and the user, and manufacturing take place in smaller units near to the point of use. Paul Goodman (1968) gives the following definition:

'Decentralizing is increasing the number of centres of decision-making and the number of initiators of policy, increasing the awareness of the whole function in which they are involved, and establishing as much face-to-face association with decision-makers as possible'.

- The use of raw materials should be based on renewable resources or rich reserves, with products that are easily recycled and economical in terms of materials during construction.
- Priority should be given to production methods that use less energy and more sustainable materials, and with transport distances reduced to a minimum.
- Polluting industrial processes and materials should be avoided, and energy based on fossil fuels reduced to a minimum.

This can be summed up by saying that an optimal ecological building industry is a cottage industry, which responds to local needs and resources. However, during the last 100 years, right up to the present moment, development has followed a path of extreme centralization.

Godfrey Boyle, author and researcher at the Open University (Great Britain), has confirmed that an industry can just as easily be too large as too small, and has concluded that for many industries the most efficient level of production lies in the region of having 10 000 users (Boyle, 1978). In Sweden they have discovered that the optimal size of a farm with cattle and pigs is the family-based farm. Shipping companies are changing from very large to medium-sized ships. Bakeries are closing down large bread factories in favour of local bakeries.

At the same time we do not really know the exact relationship between size and efficiency. It generally depends on the actual product. For example, there is perhaps no limit to how large an egg farm can be in order to optimize its efficiency. The Norwegian social scientist Johan Galtung has an interesting view on the problem:

> 'High productivity does not necessarily mean something positive. We can already see that efficiency is too high; newly completed articles have to be burned, weaknesses are built in so that the product does not last too long. There is an increasingly wound-up cycle of fashion-oriented products, which age quickly and then have to be replaced by the next fashion, leading to the time when articles are obsolete the moment they are released on the market!' (Galtung *et al.*, 1980)

Galtung's solution: 'Reduce productivity. The market cannot absorb all the products it manufactures.'

In most industrialized countries the economy includes large subsidies for energy infrastructure and road building. Taxes pay the costs for inspection and control of pollution and health problems induced by industrial activities. The cost to nature is, however, seldom accounted for. This is difficult to calculate but is, nevertheless, a debt that coming generations will have to pay for. Besides measurable pollution, other factors must be included, such as the lost renewable supply of wood fuel from a well-balanced forest that has to be sacrificed so that iron ore in mountainous areas can be harvested. Such a calculation is very complex and is beyond the scope of this book.

The price tag in the shop is therefore anything but realistic. For example, the price difference between a solid board of timber and a cheap sheet of chipboard coated with a plastic laminate has probably already been paid for by the customer before they even enter the shop. Green taxation can, to some extent, offset this by internalizing some of the resource and environmental costs.

3.4 RECONNECTING TO THE NATURAL SYSTEMS

When the Dutch mission, the Herrnhuten, came to Labrador in 1771, the Eskimos lived in large family groups in houses of stone and turf. The rooms were small and warmed by lamps fuelled by blubber. One of the first things that the new settlers did was to introduce a new form of house. They built timber houses with large rooms heated by wood-fired iron stoves. This had a radical effect on the whole Eskimo society. They had earlier obtained fuel oil from seals by hunting. The meat provided food and the hides could be used for clothes and boats. The change of house made fetching wood a critical task. The forest was a long way away and the sleigh dogs needed to eat more meat, so seal hunting had to increase as well as wood gathering. The need for wood became so great during winter that it took longer time than all other tasks put together. Despite their efforts it became clear that the new timber houses could not give the same warmth and comfort as the original earth houses (Arne Martin Claussen).

This represents a kind of miniature of today's industrial thinking. Society devours virgin materials, consumes them in the production process, often with a very low level of recycling, and leaves the waste to nature. The industrial culture of a throughput economy is the antithesis of nature's diligence based on restricted resources. Nature's method is that of integration and optimization for the natural environment as a whole. Efficiency is based on the greatest variety of species where each has its own special place. There is a continuous interplay between all the different species.

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4 The chemical and physical properties of building materials

Building components are produced in different dimensions and forms. A block is traditionally defined as a building stone that can be lifted with two hands, whilst a brick can be lifted with one. Two people are needed to carry a building board. A new category has now become common: large building elements that can only be moved and positioned by machines. Each group of materials and components creates its own particular form of working.

Properties of materials are chemical and physical. Chemistry describes a substance's elemental content and composition, whilst physics gives a picture of its form and structure. For example, as far as chemistry is concerned it does not matter whether limestone is in powder or boulder form; in both cases, the material's chemical composition is calcium carbonate. In the same way, physical properties such as insulation value or strength are independent of chemical composition.

In conventional building it is primarily the physical properties that are considered, and it is almost entirely these properties that decide what materials can and should be used. Exceptions, where the chemical properties are also taken into consideration, occur where the material will be exposed to various chemicals. Determining the material's reaction to moisture, oxygen or gases will include chemical analysis. This is much more important nowadays with increased air pollution, which contains various highly reactive aggressive pollutants.

An ecological evaluation of the production of building materials requires a knowledge of which substances are involved in the manufacturing process and how these react with each other. This gives a picture of the possible pollutants within the material, and what the ecological risks are when the material is dumped in the natural environment. Increased attention to the quality of indoor climates also creates a greater need for chemical analyses. In many cases problems are caused by emissions from materials in the building. How these react with the mucous membranes is also a question of chemistry. It has been shown that certain materials react with each other, and can thus affect each other's durability, decay and pollution potential.

4.1 AN INTRODUCTION TO THE CHEMISTRY OF BUILDING MATERIALS

There are 118 different chemical elements of which 92 occur naturally on earth. Each is represented by a single letter or two letters, such as H for hydrogen or Au for gold. Chemistry is mainly concerned with the way these elements act and combine to form compounds.

Materials usually consist of several compounds, and the picture can therefore become very complex. A traditional telephone can contain as many as 42 different elements (Altenpohl, 1980; Karsten, 1989). Materials exist as solids, liquids or gases and the same chemical compound can exist in any of these three states, depending on temperature and pressure. Water (H_2O) freezes at 0 °C and boils, or evaporates at 100 °C without changing its chemical composition.

The smallest unit a material can break down into is a molecule. Every molecule consists of a certain number of atoms. These atoms represent the different elements and can be obtained through chemical reactions ().

Relative atomic weight

Each element has its own characteristic atomic structure, mainly described by its weight: the relative atomic weight. Hydrogen has the lowest relative atomic weight, 1, while oxygen has a relative atomic weight of 16.

The molecular weight of water is found through adding up the different atomic weights:

$$H_2O = H + H + O = 1 + 1 + 16 = 18 \qquad (1)$$

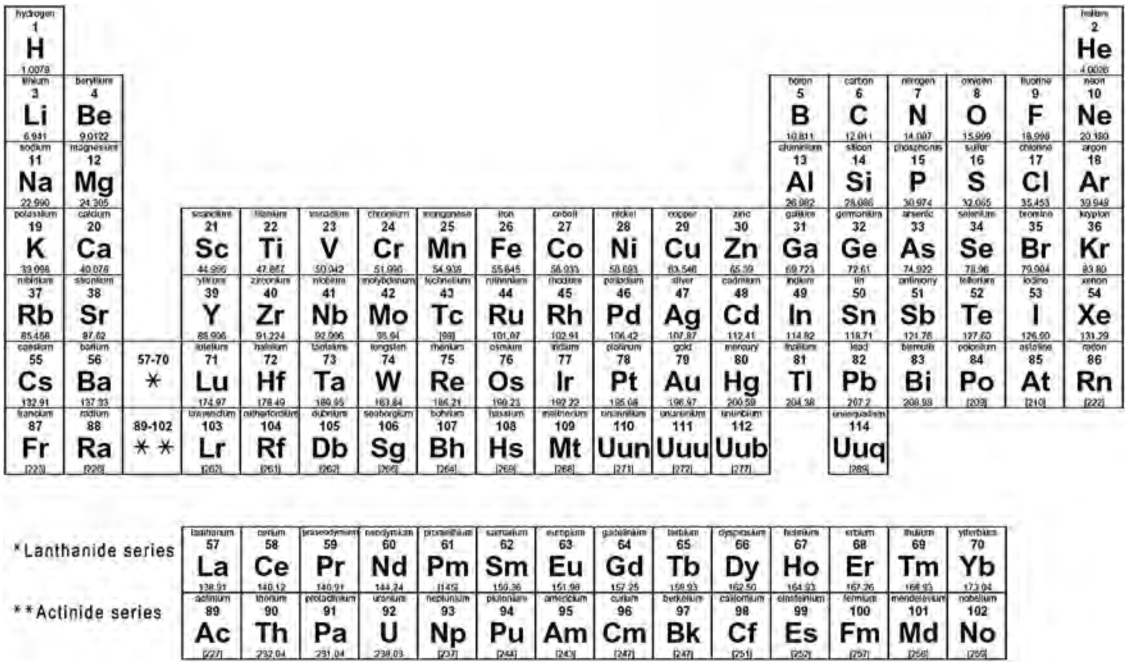
Calcium carbonate ($CaCO_3$) consists of calcium (Ca), with a relative atomic weight of 40, carbon (C) with a relative atomic weight of 12, and oxygen (O) with 16. The relative molecular weight is therefore:

$$CaCO_3 = Ca + C + O + O + O = 40 + 12 + 16 + 16 + 16 = 100 \qquad (2)$$

The relative atomic weights of the different elements are given in the periodic table (Figure 4.1). The elements are also given a ranking in the table of 1–118. The number of the elements in the ranking order is equivalent to the number of protons in the nucleus of the atom.

4.1.1 Radioactivity

In the heaviest atoms there is often a large inner tension. They may thereby emit radiation into their surroundings. There are three different forms of radiation: alpha, beta and gamma radiation. Gamma radiation is pure electromagnetic radiation. It can penetrate most materials in the same way as X-rays. Alpha and beta radiation are caused by the atom breaking down, reducing the size of the nucleus. Radium (Ra) with the atomic number 88, will decay by radiation through a number of stages and finally become lead (Pb) with the atomic number 82. This process takes thousands of years.



1 H																		2 He
3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-70 *	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-102 **	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq				

*Lanthanide series	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
**Actinide series	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

4.1

The periodic table.

4.1.2 Weights of the substances in a chemical reaction

For a chemical reaction to take place substances must have the necessary affinity with each other, and can be mixed in specified proportions. Only certain substances react together in given circumstances, and the different molecular combinations that result, always have the same proportion of elements as the original substances.

A chemical combination between iron (Fe) and sulphur (S) making ferric sulphide (FeS) will follow their atomic weights:

$$56 \text{ g Fe} + 32 \text{ g S} = 88 \text{ g FeS} \qquad (3)$$

If we begin with 60 grams of Fe, there will be 4 grams of Fe left over after the reaction has taken place. These leftovers may be important. In the production of polymers, the remaining products from the reaction are called residual monomers. These by-products usually follow the plastics in the process as a sort of parasite, even though they are not chemically bound to them. This physical combination is very unreliable and can lead to problematic emissions in the indoor climate.

It is possible to calculate how much of each of the different elements is needed to produce a particular substance. In the same way we can, for example, calculate how much carbon dioxide (CO_2) is released when limestone is heated up:

$$CaCO_3 \rightarrow CaO + CO_2 \qquad (4)$$

$CaCO_2$ has the following weight, through adding the relative atomic weights:

$$\begin{aligned} &40 + 12 + 16 + 16 = 100 \text{ g} \\ &CaO \text{ is } 40 + 16 = 56 \text{ g} \\ &CO_2 \text{ is } 12 + 16 + 16 = 44 \text{ g} \end{aligned} \qquad (5)$$

This means that 44 g of CO_2 are given off when 100 g of limestone is burned.

4.1.3 Supply and release of energy in chemical reactions

The conditions governing how a chemical reaction takes place are decided by the physical state of the substances. There are three different states: the *solid* state which is characterized by solid form, defined size and strong molecular cohesion; the *gaseous* state which has no form and very weak molecular cohesion; and the *liquid* state, which is somewhere between the two other states.

When heated, most substances change from the solid state through the liquid state and to the gaseous state. In a few cases there is no transitional liquid state, and the substance goes directly from the solid to the gaseous state. As molecular cohesion is weakened in the higher states, the majority of chemical reactions need a supply of heat. The amount of heat energy supplied is dependent upon the temperature needed to make the substances transform into the higher state, i.e. the substance's boiling point.

However, there are also chemical reactions which emit energy (Table 4.1). When water is mixed with unslaked lime (CaO), slaked lime ($Ca(OH)_2$) is formed by the release of a great deal of heat. If slaked lime is then burned, unslaked lime will form and water will be given off in the form of steam. The energy supply in this reaction is exactly the same as the amount of energy released in the first reaction.

Each substance has a given energy content, known as the element's cohesive energy. If the energy content in the original substances of a chemical reaction is greater than the energy content of the resultant substances, then energy is released as heat. This is called an exothermic reaction. In an endothermic reaction, energy must be supplied to the reaction. Exothermic reactions usually occur in nature; endothermic reactions are usual in industrial processes.

It is not only energy in the form of heat that can stimulate chemical reactions: radioactivity, electricity and light can also do this. This includes sunlight which can initiate a number of chemical processes in many materials.

One of the most important rules in chemistry is: 'Within a chemical reaction the sum of the mass energy is constant'.

Table 4.1 *Classification of volatility for organic substances*

Type	*Boiling point*
VOC Volatile Organic Compounds	Below 250 °C
SVOC Semi-Volatile Organic Compounds	250–380 °C
POM Particle-bound Organic Compounds	Above 380 °C

4.1.4 Other conditions for chemical processes

Other factors also affect the reactions process. The solidifying process of chalk ($CaCO_3$) is an example:

$$Ca(OH)_2 + H_2O + CO_2 \rightarrow CaCO_3 + 2H_2O \tag{6}$$

Note that solidifying is reduced at lower temperatures; and a higher concentration of carbon dioxide accelerates the chemical reaction, even if not all of it is used in the reaction or is part of the final product.

The size of the particles also plays a role: the finer the particles, the greater the surface of the materials, making the reaction quicker. Finely ground cements, for example, have a shorter setting time. In a few chemical reactions with gases, air pressure plays an important role – pressure decides the weight of the gases.

In chemistry there are also catalysts, which increase the rate of the reaction without actually 'chemically' taking part in it. In an animal's digestion system catalysts are known as vitamins and play a vital role in a whole series of processes. Catalysts play an important part in many industrial processes.

A chemical reaction can, in principle, be reversed, and must be seen as a reaction in equilibrium. Chemical compounds can be stable, metastable and unstable. Life would not have been possible without metastable systems.

4.1.5 The elements

Ninety-nine per cent of the Earth's crust consists of ten elements. The other 1% consists of, amongst other elements, carbon, which is a condition for biological processes.

There is a difference between organic and inorganic compounds. Carbon is the basic element in all life, and is present in all organic

Table 4.2 *The most common elements*

Element	*Chemical symbol*	*Per cent of Earth's crust*
Oxygen	O	49.4
Silicon	Si	25.8
Aluminium	Al	7.5
Iron	Fe	4.7
Calcium	Ca	3.4
Magnesium	Mg	1.9
Sodium	Na	2.6
Potassium	Ka	2.4
Hydrogen	H	0.9
Titanium	Ti	0.6
Total		99.2

compounds, including lifeless compounds such as oil and limestone that were originally created from decomposed living organisms.

There are 500 000 carbon compounds. They include many compounds not found in nature, including modern plastics. The inorganic compounds number approximately 80 000.

4.2 IMPORTANT FACTORS IN THE PHYSICS OF BUILDING MATERIALS

In every building project it is important to have a clear picture of a material's physical properties. There will be different demands on the different groups of materials. The following are the central technical specifications (see also Table 4.3):

- *Weight* indicates what structural loading can be anticipated in the building, which building techniques can be used, etc. Each material has its characteristic density.
- *Compressive strength* is an expression of how much pressure the material tolerates before failing, and is of particular importance in the design of columns, arches and other vertical structural elements.
- *Tensile strength* expresses how much a material can be stretched before collapsing. This is important for the calculation of horizontal structural elements such as beams or floors, and suspended structures.
- *Thermal conductivity* describes a material's ability to conduct heat. It describes the insulating properties that can be expected of this material as a layer within an external wall for example. The conductivity of a material is dependent upon the weight of the material, the temperature, its moisture content and structure.
- *Thermal capacity* of a material is its ability to store heat or cold. This often helps to even out the temperature swings in a building and also in many cases reduce energy consumption. Thermal capacity is directly proportional to a material's weight.
- *Air permeability* indicates how much air will move through a material under different pressure conditions. It depends upon a material's

Table 4.3 *Aspects in the physics of building materials*

	Structural materials	*Climatic materials*	*Surface materials*	*Surface treatment*
Weight	x	x	x	
Compressive strength	x	(x)	(x)	
Tensile strength	x	(x)	(x)	
Thermal conductivity	(x)	x	(x)	(x)
Thermal capacity	(x)	x	(x)	
Air permeability	(x)	x	(x)	
Vapour permeability	(x)	x	(x)	(x)
Moisture regulating quality	(x)	x	x	(x)

Notes: x: primary aspect; (x): secondary aspect.

porosity – the size and the structure of its pores. The moisture content of the material also plays an important role since water in the pores will prevent air passing through. Air permeability is particularly important when making a building airtight.

- *Vapour permeability* gives the equivalent picture of water vapour penetration under different pressures. This can vary according to the material's moisture content and temperature, and is a decisive factor in the prevention of damage caused by damp.
- *Moisture regulating quality* describes a material's ability to absorb and release humidity. A measurement often used for this is the moisture buffer value (MBV). It is closely related to the vapour permeability, but also to density, porosity and sorption properties. Materials with a high moisture buffer value can be used positively to reduce the humidity in the indoor climate. This can both improve health and reduce building damage caused by humidity, including growth of moulds and fungi as well as humidity-induced chemical reactions (Rode *et al.*, 2005). In order to be effective, the paint or surface treatment on such materials must also have a high vapour permeability.

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PART 2 THE FLOWER, IRON AND OCEAN: RAW MATERIALS AND BASIC MATERIALS

5 Water and air

Water and air are necessary for all life and therefore for all animal and vegetable products; they are the main constituents of many materials. Water can dissolve more chemical compounds than any other solvent and is used a great deal in the painting industry. Water is essential in concrete even though much of it evaporates as part of the setting process. Air is also an important component in the chemical processes required for the setting of most concretes. It is also the essential constituent of insulation materials. The majority of industrial processes also use great amounts of water for cooling, cleaning, etc.

Clean air and pure water are limited resources in many places. During recent years large parts of the European continent and several other densely populated regions have experienced drastic disturbances in the water situation including widespread pollution of ground water. It is expected that this will accelerate with changing precipitation rates and patterns as a result of global warming.

5.1 WATER

Water is seldom 'just water'. It nearly always contains other substances to some degree such as calcium, humus, aluminium and nitrates. The quality of water is important not only for drinking, but also as a constituent in building materials. For example, water with a high humus content produces bad concrete, since humus acids corrode the concrete.

The terms 'hard' and 'soft' water are well known. Hard water contains larger amounts of calcium and magnesium, typically 180–300 mg/l, than soft water, which contains approximately 40–80 mg/l. Very soft water will have a dissolving effect on concrete.

Water also has different levels of acidity which is expressed in the pH-scale with values from 0 to 14. The lower the pH value, the more acidic the water. A pH value of 6.5–5.5 has a slightly aggressive effect on concrete and materials containing lime, whilst a pH value under 4.5 is very aggressive. Marsh water contains large amounts of sulphuric acid and is therefore unsuitable for most uses. Free carbonic acid, found in most water, attacks lime and corrodes iron. Sulphates in water, especially magnesium sulphate in salt water, are also corrosive and attack lime products.

IMPROVING COLLOIDAL PROPERTIES

Energized water (E-water) is water that has been treated in a *levitation machine*. The machine is a hyperbolic cylinder where the water is spun in a powerful and accelerated spiral movement. The process was developed by Wilfred Hacheney in Germany in 1976. When this water is used in cement, it has been found that the material assumes an amorphous mineral structure as opposed to ordinary crystalline concrete. This is probably due to increased colloidal properties, i.e. reduced tension in the water that increases contact between the water and the concrete particles. The practical consequences are better compressive and tensile strength and a higher chemical stability, including against air pollution. According to research the level of tolerance can drop to pH2, and at the same time the proportion of water and the setting time can be reduced. More conventional ways of increasing the colloidal properties usually entail mixing in small quantities of waterglass, natron and/or soda.

5.2 ICE AND SNOW

The potential of snow as an insulating material against walls and on roofs has been used in the north throughout history. One of the main reasons for having a grass roof is that in appropriate climates it retains snow for longer. Ice is also a structural building material of interest in colder climates. The former Soviet Republics have a special category of engineering, 'engineering of glaciology': the design of ice structures such as roads and bridges in areas of permafrost. Many of these structures are now in danger due to climate warming. In recent years there has also been a keen interest in ice hotels, both in Scandinavia as well as Canada, Romania and Switzerland. These are seasonal, and as long as natural ice is used is an excellent environmental material.

5.1

Ice hotel in Jukkasjärvi, Finland. Design by KTH students. Photo: Ben Nilsson/Big Ben Productions.

5.3 AIR

5.2

Ice church in Jukkasjärvi, Finland. Architects: Vonk, Berg, de Schoot and Vroom. Photo: Big Ben Productions.

In the Earth's atmosphere the percentage by weight of the different gases is as follows: Nitrogen 78%, oxygen 21%, argon 0.93%, carbon dioxide 0.038%; plus smaller amounts of hydrogen, neon, helium, krypton and xenon, as well as water vapour and various pollutants.

At very low temperatures air becomes a slightly blue liquid. From this state oxygen and nitrogen can be extracted by heat. Nitrogen can be used for the production of ammonia by heating hydrogen and nitrogen to 500–600 °C under a pressure of 200 atmospheres and passing it over a catalyst, usually iron filings. However, today ammonia is mostly produced from natural gas. Ammonia is an important ingredient in the production of waterglass via soda, and as the main raw material for the production of ammonium salts, which are used as flame retardants in some insulation products. By reacting with hydrocarbons it forms amines that are used in the production of a whole series of plastics.

When a material oxidizes it forms a chemical compound with oxygen. This is an exothermic reaction. In construction this is a very common process in metals, known as rust or corrosion. The process is electrolytic. In many cases this oxidization is not a welcome process, so metals in construction are often treated with a protective coating. Rust on reinforcing bars for concrete, on the other hand, is to an extent welcome since it increases the bond with the concrete.

Other compounds in the air can also break down building materials, including natural carbon dioxide and air pollutants, such as sulphur dioxide and soot.

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6 Minerals

Most of our planet is made up of inorganic, mineral materials. Stone consists of minerals in the form of crystals, and it is estimated that there is 4000 times as much solid rock on the earth as there is water in all the oceans.

There are thousands of minerals. They can be characterized by colour, lustre, translucence, weight, hardness, their ability to split, and also by chemical formulae, each type of crystal having its own unique chemical structure. In common rock types there are only a few hundred different minerals, and in one single species there are seldom more than four or five different minerals. Granite is made up of the minerals quartz, feldspar and mica, the latter contributing sparkle. In only a few cases can minerals be found in a pure state.

The first use of minerals can be traced back to Africa in the production of colour pigments. These were retrieved from the earth through a simple form of mining.

In chemistry, minerals are classified according to their chemical composition. The most important groups include pure compounds: sulphides, oxides, carbonates and silicates. Most widespread are the silicates, whilst it is mainly oxides and sulphides that are used as ore for the extraction of metals. To simplify the picture one can reduce minerals into two groups: *metals* and *non-metals*.

The purer the mineral when extracted, the easier it is to use. However, most minerals are extracted from conglomerate rocks or different types of loose materials.

Certain minerals have a tendency to occur together in the natural environment. When looking for a certain mineral, it is usually very straightforward to work out where to find it.

6.1 METALLIC MINERALS

Some minerals have a chemical composition that makes it possible to extract metals from them. These are usually mixed with other minerals in the ores (see Table 6.1). The most common ore from which aluminium is extracted is bauxite, which contains iron as well as aluminium oxides.

In earlier times metals were worth a great deal because they were often inaccessible and required complicated working techniques. At

Table 6.1 *Metals, their ores and their use in building*

Metal	*Ore*	*Use in building*
Aluminium (Al)	Bauxite, nepheline, kaolin	Light structures; roof covering; wall cladding; heat-reflecting foils and vapour barriers; window and door construction and furniture; guttering; additive in aerated concrete
Antimony (Sb)	Stibnite	Pigment (yellow)
Arsenic (As)	Arsenopyrite	Ingredient in timber impregnation
Cadmium (Cd)	Sphalerite	Pigment (red and yellow); stabilizer in polyvinyl chloride; alloys
Chrome (Cr)	Chromite	Alloy in stainless steel; pigment (yellow and green); ingredient in timber impregnation
Cobalt (Co)	Cobaltite	Pigment (white); siccatives, colouring of glass
Copper (Cu)	Chalcocite, chalcopyrite	The most important constituent in bronze; roofcovering; door and window furniture; guttering; ingredient in timber impregnation
Gold (Au)	Gold ore	Colouring of glass; vapourized onto windows as reflective coating
Iron (Fe)	Hematite, magnetite	The most important constituent in alloy steels; balconies; industrial floors; pigment (red, yellow etc.); ingredient in timber impregnation
Lead (Pb)	Galena	Roof covering; flashing; pigment (white); siccatives; additive in concretes
Magnesium (Mg)	Saltwater, dolomite	Alloys, potentials as for aluminium
Manganese (Mn)	Braunite, mangenite, pyrolusite	Part of alloy steel; pigment (manganese blue); siccatives
Nickel (Ni)	Pentlandite	Alloy in stainless steel; galvanizing of steel; pigment (yellow, green and grey)
Tin (Sn)	Cassiterite	Stabilizer in polyvinyl chloride; colouring agent in glazing for ceramics; ingredient in timber impregnation; catalyst in the production of silicone and alkyd
Titanium (Ti)	Ilmenite, rutile	Pigment (white)
Zinc (Zn)	Sphalerite	Zincing/galvanizing of steel; roof covering; pigment (white); ingredient in timber impregnation; additive in concretes
Zirkonium (Zr)	Zircon	Siccatives

first they were used for weapons and tools. Through the great technological changes of the industrial revolution, metals have become essential in the building industry; in particular steel and aluminium, followed by copper and zinc. Uses are spread over a wide spectrum from roof-laying and window frames to structures, nails, fixtures, pipes, and colours in plastic, ceramics and paints.

In many cases, metals can be replaced with other materials such as timber, cement products, etc.

During the extraction of ore, the mountains of slag and dust produced causes environmental problems since they often contain problematic residues. Extraction, especially shallow open cast mining, also leaves huge scars in the landscape that require filling and planting to restore afterwards. Even after much work it can be difficult or even impossible to rehabilitate or re-establish the local flora and fauna and achieve an acceptable water table level.

Table 6.2 *Important metal alloys*

Alloy	*Constituents*	*Use in building*
Bronze	Copper (more than 75%)	Roof covering
	Tin (less than 25%)	
Steel	Iron (85–98%)	Structures, floors, walls and roofs; reinforcement in concrete; roof covering; wall cladding; guttering; door and window furniture; nails and bolts (galvanized or zinced)
	Manganese (0.1–0.5%)	
	Nickel (1–10%)	
	Silicon (0.5–1.0%)	

All industries that deal with metal extraction or smelting are environmental polluters (Table 6.3). This is partly through the common energy pollution from burning fossil fuels and partly through material pollution from the smelting process. Ores often contain sulphur, and during smelting huge amounts of sulphur dioxide are released. It is usual for this to be extracted and used in the production of sulphuric acid. Toxic heavy metal residues such as mercury, cadmium and lead are also common.

The consumption of energy for the extraction and refining of metals from ore is very high (Table 6.4). All metals can, in principle, be recycled. Through material recycling of steel, copper, zinc and lead from waste, the energy consumption can be reduced by 20 to 40% and for aluminium by 40 to 90%. The metal industry also has a high potential to increase efficiency by using excess heat, which can be distributed as district heating.

Once in the buildings themselves, metals cause relatively few environmental problems, except for particles that are washed off the

Table 6.3 *Material pollution from the production of metals*

Metals	*Boiling point (°C)*	*Emissions*
Aluminium	2057	PFCs, PAHs, Al, F, CO_2, SO_2, dust
Cadmium	767	Cd, SO_2
Cast iron	up to 3000	CO_2, SO_2, dust, Ar (when smelting scrap iron)
Chrome	2200	Cr
Copper	2310	SO_2, Cd
Lead	1620	Pb, Cd, SO_2
Nickel	2900	Ni, SO_2
Steel	1535	CO_2, Pb, Hg, Cd
Zinc	907	Pb, Hg, Cd, SO_2
Zincing		Cr, Fl, phosphates, cyanides, organic solvents
Galvanizing		Cr, Fl, phosphates, cyanides, organic solvents

Note: The boiling point indicates the risk of vapourizing through different processes, such as when making alloys.

Table 6.4 *Embodied energy in important metals*

Metal	*From ore (MJ/kg)*	*Recycling 50% (MJ/kg)*	*Recycling 10% (MJ/kg)*
Aluminium	165–260	89–95	13–30
Steel	21–25	18	6–10
Copper	80–125	55	
Zinc	47–87		

surface when exposed to different weather conditions. Roofing, flashings and metallic salts used in the impregnation of timber can pollute ground water and soil. Large amounts of metal, as in reinforcement for example, can lead to a stronger electromagnetic field in the building.

As waste products, metals exposed to water release particles into soil and water, which can then harm many different organisms. It is important to note that pollution due to metals is irreversible. Metals left in the natural environment will always be there – they do not decompose. Even if the present discharges are reduced, the total amount of metals ending up in the environment will still be increasing. Recycling metals, however much, only postpones the inevitable pollution.

Iron, aluminium, magnesium and titanium can be considered relatively 'benign' metals. Even though the environmental consequences of their extraction and production are still quite severe, they are not particularly toxic. Their recycling potential is high and they are based on relatively rich reserves (see Table 1.1 in Chapter 1).

Chrome, nickel, copper and zinc, however, should be used very sparingly or not at all. Cadmium and lead should be avoided completely.

6.1

Extensive extraction of minerals can cause damage to local biotopes and ground water.

All metals should, in the long-term, be used within closed cycles in order to maximize recycling and minimize losses during production or the life of the building.

6.1.1 Raw materials

Metals have limited reserves and demand exceeds the maximum possible supply of scrap, for steel by a factor around two. On current statistical predictions, iron reserves will last 95 years, aluminium 141 years, copper 31 years and zinc 22 years (US Geological Survey, 2007). These statistics do not take into account an expected increase in consumption. The growth rate in use of aluminium for example is now 6% per year, and of iron 10%.

The production of aluminium is based on bauxite, which contains 40–60% aluminium oxide. Ninety per cent of the bauxite reserves are in countries with low and medium levels of industrialization, whilst the same proportion of extracted aluminium is used in highly industrialized countries. There are also other sources of aluminium such as kaolin, nephelin and ordinary clay. In the former Soviet Republics bauxite is scarce, so aluminium oxide is extracted from nephelin, although it is much more expensive to extract aluminium from these minerals than from bauxite.

Probes are now being made to find new sources of iron ore, and have resulted in the discovery of interesting sources on the ocean floor – the so-called iron nodules. These also contain a large amount of manganese. Extraction of iron from peat bogs is also being considered. More recycling of scrap steel would help and it is also possible to use alternative metals. There are alternatives for most metals and alloys except chrome, which is essential in stainless steel.

6.1.2 Recycling

Metals corrode, and 16 to 20% of the total iron content effectively disappears. Chemical corrosion is an oxidation process and occurs mainly in the presence of water and oxygen. Copper, aluminium and chrome are relatively resistant to corrosion. Metals are also attacked by acids: carbonic acid from carbon dioxide and water, and sulphuric acid. Iron, aluminium and magnesium are those most affected. Materials containing lime can attack metals, particularly aluminium, zinc and lead. Electro-corrosion can occur with certain combinations of metals.

Steel structures in heavy sections are usually easy to disassemble; and as they are most often produced in standardized dimensions they are quite easy to re-use. In reinforced concrete, where the steel content can be up to 20%, material recycling is the only alternative and the process is relatively expensive and complicated. Copper in electric cables and tin in tin cans make it near impossible to recycle the steel in these products. Another issue is that waste metal often has a surface treatment that can lead to complications.

Metals and alloys that are finally melted from waste can be recycled by being added to new products in varying proportions, from 10 to 100% depending upon the end product and its quality requirements.

Steel and aluminium alloys can only be used for similar alloy products; whereas copper, nickel and tin can be completely reclaimed from alloys in which they are the main component. Copper, for example, is removed from brass through an electrolytic process.

The technology for smelting is relatively simple. Breaking down alloys electrolytically and further refining, casting or rolling techniques require much more complex machinery.

6.2 METALS IN BUILDING

6.2.1 Iron and steel

Iron was used in prehistoric times. Iron has been found in meteorites pure enough to be used without refining. Smelting iron from iron ore has been carried out for at least 5000 years. The first appearance of iron as a building material was in classical Greece, for reinforcing stone lintels and architraves. Uses in cramps, pivots, hinges and locks have been widespread. However, it is only from about the eighteenth century that we have seen more widespread uses for balustrades, balconies, furniture, stairs and various decorative items. The first structural iron girder was manufactured by Charles Bage in 1796 in England, and was used in a five-storey linen mill.

Whilst cast iron contains a large proportion of carbon, steel is an iron product with a carbon content of less than 2%. Towards the end of the nineteenth century steel became a rival to (and gradually replaced) the more brittle cast iron. Whole buildings with a steel structure started to appear then. Today, steel is the only iron-based material used in the building industry. It is possible to use about 20 different alloys in steel, and up to 10 can be used in the same steel. Particularly strong steel is formed by alloying it with small amounts of nitrogen, aluminium, niobium, titanium and vanadium. Normal construction steel such as reinforcing bars, structural elements, wall and roof sheeting does not usually contain alloys. Sheeting products are protected against corrosion by a protective layer of aluminium or zinc. Facing panels in aggressive environments are often made of stainless steel; which is 18% chrome alloy and 8% nickel. By adding 2% molybdenum alloy, an acid-resistant steel can be produced.

As a resource, iron ore is a fairly ‘democratic’ material, being spread quite evenly throughout the world; it is extracted in over 50 countries. Easily available reserves are, however, diminishing rapidly, and some of the alloy metals required (e.g. nickel and zinc) have very limited reserves.

Coal is an important element and generally a prerequisite for the production of cast iron from iron ore. The exception, where the reduction process uses natural gas, requires ore with a very high iron content.

Rock iron ore is extracted by mining; peat bog iron ore is much more accessible and generally the dominant source in earlier times. It lies in loose agglomerations in swamps or bogs. To find it, the bog was probed with a spear or pole. Where there is resistance to the spear, it can be assumed that there is ore. There may even be small traces of iron filings when the pole is removed.

The extraction of iron ore usually takes place in open quarries and extends over large areas, which means that the groundwater situation can change and local ecosystems can be damaged. One ton of iron ore usually produces 5 to 6 tons of waste materials. Extraction of coal in open quarries or deep mines causes similar environmental damage.

The conversion from iron ore to steel requires a series of processes. They begin with the breaking up of the ore, then cleaning, followed by sintering. The iron is smelted out and reduced in a blast furnace at 1700–1800 °C. A large, modern blast furnace can produce 1000 tons of pig iron every 24 hours. The amount of air needed is four million cubic metres, and the cooling water is equivalent to the amount a small town would use. It takes 440–600 tons of coal to produce 1 ton of iron. The total amount of coal needed can be halved if an oil spray is injected into the furnace. Coal is used in the process to remove oxygen from the ore by forming carbon dioxide, leaving the pig iron behind. Limestone is added to the blast furnace charge in order to bind ash, silica, manganese, phosphor, sulphur and other impurities. This slag can, in turn, be used as pozzolana in the production of cements, see page 186–187.

Steel can be made from pig iron and steel scrap. Most of the carbon in the iron is released through different methods, e.g. oxidizing. This is done in blast furnaces or electric arc furnaces. The latter is often used in smaller-scale facilities, consumes less energy, however mainly as electricity, and represents 30–40% of the world's production today. Steel production in electric arc furnaces can also be based on 100% steel scrap, while other production methods only permit a fraction of scrap. Finally, the steel is rolled out to produce stanchions, beams, pipes, sheeting and nails.

Large amounts of the greenhouse gas carbon dioxide, as well as sulphur dioxide, fluorine compounds, dust and a wide range of heavy metals are emitted in the production of pig iron. The carbon dioxide comes partly from the combustion of coal in the reduction process and also as chemical emissions from the burning of admixtures of limestone. The net emission of carbon dioxide as well as sulphur dioxide can be significantly reduced by replacing mineral coal with a maximum of charcoal in the reduction process (30–40%). This is done in Brazilian iron production. The charcoal can even be mixed in with wood chips to a certain extent.

In the production of steel emissions of carbon dioxide will be large, but in general significantly lower for electric arc furnaces than for blast furnace technology (Kram *et al.*, 2001). Other available methods for reducing energy consumption and carbon dioxide emissions in steel production include *direct reduction* and *iron bath smelting* but these are not yet economical.

The toxic element arsenic is well bound in the iron ore, but with a second smelting from steel scrap a good deal is released. Production from scrap iron also causes emissions from other compounds in the scrap, and considerable release of polycyclic aromatic hydrocarbons (PAH) and dioxins can be expected. When producing from stainless steel, there will be a larger release of nickel and chrome.

Steel scrap is virtually inert, but ions from iron and other metal alloys can leak into water and soil. Serious pollutants can also include waste materials from surface treatments, paint or fire protection coatings.

Protection against corrosion

When ordinary steel is exposed to humid air, water, acids or salt solutions, it rusts. This is hindered by coating it with zinc, tin, aluminium, cadmium, chrome or nickel or a combination of these, usually through galvanizing.

For zinc coating, metal is dipped into molten zinc at a temperature of at least 450 °C. Zinc and iron bind with each other giving a solution that forms a hard alloy layer. Galvanizing is an electrolytic process. The metal to be coated acts as a cathode, and the material coating acts as anode.

These two processes, zinc coating and galvanizing, are considered serious environmental polluters. In both cases there is an emission of organic solvents, cyanides, chrome, phosphates, fluorides, etc., mainly in the cleaning water. These pollutants can be precipitated in sludge form, but then still have to be handled as hazardous waste. Many galvanizing industries do not do this. In the largest Norwegian zinc plant, the toxic sludge, named Jarosite, is pumped into mountain waste caverns for permanent disposal.

One method for relatively pollution-free galvanizing is a process making use of the natural occurrence of magnesium and calcium in seawater. The technique was patented in 1936 and quite simply involves dropping the iron into the seawater and switching on an electric current to give it a negative charge. This method has proved effective for underwater sea structures. It is, however, not known to what degree this technique gives lasting protection from corrosion for metal components that are exposed to conditions on land.

Zinc ions are washed off roof surfaces by rain. This can be halved by having small amounts of aluminium added in the galvanizing process. Treating surfaces of steel and metals with a ceramic coating could give even better results environmentally. These methods are currently only used on materials in specialized structures.

Steel reinforcement is not galvanized. Concrete provides adequate protection against corrosion. But even concrete disintegrates over time, and the reinforcement is then exposed. Correct casting of concrete should give a functional lifespan of at least 50 years.

The most corrosive environment for galvanized iron and reinforced concrete structures is sea air, the air surrounding industrial plants, and car traffic. As a result of climate change, chemical damage to steel is expected to increase in the northern part of Europe and to decrease in the southern part. On the other hand, chloride-induced zinc corrosion within some hundred of metres from the sea is expected to increase in all coastal areas (Noah's Ark, 2006).

6.2.2 Aluminium

Aluminium is a relative newcomer amongst metals and was first produced in 1850. Since an aluminium structure weighs only about one third of a corresponding steel structure, it is used in light constructions and as roof and wall cladding. Use in the building industry is increasing rapidly.

Aluminium is usually extracted from the ore bauxite. A large part of global reserves is situated in rainforest areas of Brazil, Surinam and Venezuela. Extraction occurs mainly in open cast quarries. Production entails a highly technological process of which electrolysis is an integral part. Efficient production plants require particularly high capital investment; countries with large reserves of bauxite but low levels of industrialization have mostly had to export the ore rather than refine themselves. This is also because of the very large amount of energy that is required to produce aluminium. Still, it is probable that today's large aluminium-producing plants in the USA, Canada and Northern Europe will, like other industries, progressively relocate to developing countries.

Aluminium is produced in two stages after extraction of the bauxite ore. Aluminium oxide is first extracted by heating it to between 1100 °C and 1300 °C in the presence of sodium hydroxide and lime. This is known as 'calcination'. The oxide is then broken down in an electrolytic bath at around 950 °C with sodium and fluorides. The pure aluminium is deposited on the negative pole, (cathode) and on the positive anode, oxygen is released which combines with carbon monoxide and carbon dioxide. The anode consists of a paste mixture of powdered coal and tar – for every kilo of aluminium, half a kilo of paste is required. A huge amount of water is used too.

The aluminium is then formed into sheets. The surface of aluminium oxidizes naturally, providing it with protection. However, this thin layer is attacked by chlorides when in the proximity of salt water and by sulphur dioxide in urban environments, so it is common to add an extra layer by the anodizing process. This can include a colour and often gives a metallic sheen to the surface. An alternative plastic coating is termed powdercoating.

The processes in the aluminium industry release large amounts of the greenhouse gases carbon dioxide and perfluorocarbons (PFCs). These latter are especially potent and generate the equivalent of 2.2 metric tons of carbon dioxide for every ton of primary aluminium. In addition, the process releases large emissions of sulphur dioxide, polyaromatic hydrocarbons (PAHs), fluorides and dust. PAH substances, fluorine and aluminium ions remain in the sludge and slag from the production processes. This especially tends to cause problems in ground water where deposits have to be stored in landfills.

Recycled aluminium can be used a great deal in cast products. Aluminium waste is recycled by smelting in a chloride salt bath at 650 °C, which at best only requires 7% of the energy needed for the production from ore. The waste aluminium has to be pure; this is often complicated by residue from coatings such as powdering – and by ongoing efforts to increase the material quality by developing new aluminium alloys (Azar *et al.*, 2002). Recycling of aluminium requires a great deal of transport however because of centralized production.

6.2.3 Copper

Copper was probably the first metal used by mankind. The oldest copper artefacts we have were made about 7000 years ago in Mesopotamia. The earliest known use in buildings is as cramps to fix stone blocks in the Valley Temple of Chephren in Egypt from 2500 BC (Wright, 2005). An early development was the invention of bronze, produced by adding tin to create a harder metal.

There are many examples of bronze being used in ancient buildings. The roof on the Pantheon in Rome was covered in bronze sheeting. Copper has always been an expensive material and is found mainly in churches and larger buildings.

The most important alloy, brass, consists of 55% copper and up to 45% zinc, occasionally combined with other metals. It is commonly used in armatures. Copper compounds are also used in a variety of timber impregnation treatments.

Copper ore is extracted in the Congo, Zimbabwe, Canada, USA and Chile and entails a heavy burden on the natural environment. Reserves are very limited. Large quantities of sulphur dioxide are emitted during copper smelting. Modern plants resolve this problem by dissolving the ore in sulphuric acid, then extracting pure copper by electrolysis.

Copper is washed off roofs by rain, especially where the rain is acid. Copper ions bind quickly in the soil and is thus not transported for longer distances.

Copper is toxic and can accumulate in animals and aquatic plants; however, unlike many other heavy metals, it does not accumulate in the food chain. Copper has a very high durability. Most copper in Western Europe is now recycled. Some, however, is re-used locally, such as thick copper sheeting.

6.2.4 Zinc

Zinc probably came in to use around 500 BC. It has commonly been used as roofing material and later to galvanize steel to provide corrosion resistance. It is also used as a pigment in paint and as a poison against mould in impregnation treatments, and is a constituent in brass alloys. Extraction of zinc causes the release of small amounts of heavy metals including cadmium. Zinc is susceptible to aggressive atmospheres. In ordinary air conditions, one can assume a lifespan of 100 years for normal coating; but only a few years near the sea air, in damp city air or industrial air. There are very limited reserves of zinc. When zinc is broken down, the zinc particles are absorbed in earth and water. In higher concentrations, zinc is considered toxic to organisms living in water. It can be recycled.

6.2.5 Secondary building metals

The following metals collectively represent a very small percentage of the use of metals in the building industry.

Lead has been in use for 4000 to 5000 years. It is not found freely in the natural environment, but has to be extracted, usually from the mineral galena – lead sulphide (PbS). The most common use of lead has been for roofing material and for detailing, but it has also been used for pipes, in Rome and Pompeii, for example. Danish churches have a total of 30 000–50 000 tons of lead covering their roofs. The paint pigment, lead white, was also very common until recently, when its toxic effect on humans was discovered. Useful lead resources are very limited.

Lead is mostly used nowadays in flashings for chimneys and around roof windows and the like. It is durable, but can still be broken down in aggressive climates. When lead is exposed to rain, small, highly poisonous lead particles are washed out into the ground water. Lead has a tendency to biological accumulation.

Cadmium does not occur naturally in a pure form, but in the compound cadmium sulphide (CdS) which is often found associated with zinc sulphide (ZnS). Cadmium was discovered in Germany in 1817, and is used as a stabilizer in many polyvinyl chloride (PVC) products. It is also used as a pigment in painting, ceramic tiles, glazes and plastics. Colours such as cadmium yellow or cadmium green are well known. The metal is usually extracted as a byproduct of zinc or lead manufacture. Cadmium has a relatively low boiling point, 767 °C, which is why it often occurs as a waste gas product in industrial processes, as well as in house fires and incinerators. Accessible reserves are very limited. Cadmium particles are washed out of waste containing cadmium. Cadmium has a tendency to biological accumulation, and in small doses can cause chronic poisoning to organisms.

Nickel is used in steel alloys to increase strength. It is also an important ingredient for stainless steel. It is used as a colour pigment in certain yellow, green and grey colours, for colouring ceramic tiles, plastics and paint. Nickel has very few accessible sources. During production of nickel large amounts of metal are liberated. Nickel is bioaccumulative and is particularly toxic for aquatic organisms. In the former Soviet Union a connection was registered between nickel in the soil and the death of forests (Törslöv *et al.*, 1985).

Manganese is a necessity for the production of steel. Between 7 and 9 kg are often required per ton of steel. It is also used in alloys of aluminium, copper and magnesium. Manganese is also a colouring pigment: manganese blue. Manganese can cause damage to the nervous system.

Chrome is used for the impregnation of timber and in stainless steel. There is no alternative to its use in stainless steel, so chrome is very valuable. Chrome compounds are bioaccumulative and are very poisonous.

Arsenic is usually produced from arsenopyrite (FeAsS). Its main use is in timber impregnation, where it is mixed with copper or chrome. Accessible reserves of arsenic are very limited. Arsenic has been the most popular poison for murder for many centuries. The metal has a tendency to biological accumulation and is extremely toxic.

Magnesium is not used very widely. It is a very light metal that can often replace aluminium. It is extracted from dolomite or from seawater and is thus the only metal with very large accessible reserves. Magnesium is not considered toxic, but during production sulphur hexafluoride (SF_6) is used as a cover gas. Sulphur hexafluoride is a potent greenhouse gas and only a part of it decomposes during the production process, whilst the rest is released to the atmosphere.

Titanium is the tenth most common element in the Earth's crust, even though accessible reserves are few. The metal has a promising future since extraction costs for other metals are increasing, but it is relatively difficult to extract and requires high energy levels to do so. Titanium dioxide is produced from ore of ilmenite ($FeTiO_3$), and over 90% is used as the pigment titanium white, usually for paints and plastics. Production of titanium oxide is highly polluting, whereas the finished article causes no problems.

Cobalt is used as a pigment and as a drying agent in the painting industry, and also as an important part of various steel alloys. Cobalt is slightly poisonous for plants and water living organisms.

Gold has a very limited use in the building industry. The most important function is the application of a thin layer on windows which then restricts the amount of sun and heat coming into a building, and to colour glass in yellow and red. Of the 80 000 tons of gold calculated to have been mined since the beginning of time, most is still around, partly because gold does not oxidize or break down and partly because of its value. Gold used in window construction is considered to have been taken out of circulation.

6.3 NON-METALLIC MINERALS

The most important non-metallic minerals in the building industry are lime and silicon dioxide (Table 6.5).

Quartz is almost pure silicon dioxide and is the hardest of the ordinary minerals. It is the main constituent of glass and silicone, and is an important ingredient in Portland cement. Pure quartz is as clear as water and is known as rock crystal. Normal quartz is unclear and white or grey, and is found in granite, sandstone or quartzite, or the sand of these rock types.

Pure limestone is a monomineral rock type of the mineral calcite. Accessible sources of limestone appear as veins or formations in many different types of rocks of different ages. Limestone is used in a variety of products; it is one of the most important construction materials in the world after sand, gravel and crushed stone. The largest consumer of limestone is the cement industry. Cement nowadays means Portland cement, which is produced from a mixture of two-thirds ground limestone, clay, iron oxide and a little quartz, heated to 1500 °C. Gypsum is added to the mixture and then it is ground to a fine cement.

Limestone is an important filler in industries producing plastics, paint, varnish, rubber and paper. Some limestone is also used in the production of glass and fibreglass to make the materials stronger. In the metal industry, limestone is used to produce slag.

In addition to quartz and limestone, there are many non-metallic minerals of rather more limited use. Important are gypsum, used in plasterboard and certain cements, potassium chloride and sodium chloride, which form the base of a whole series of building chemicals, partly in the plastics industry, and kaolin, used as a filler in plastic

Table 6.5 *Important non-metallic minerals in the building industry*

Mineral	*Areas of use*
Anhydrite $CaSO_4$	Plaster; mortars
Asbestos (group)	Thermal insulation; reinforcement in concretes, plasters, mortars, gypsum products and plastics
Borax $Na_2B_4O_7 \times 10H_2O$	Biocides; flame retardants; production of glasswool
Boric acid $B(OH)_3$	Biocides; flame retardants
Calcium silicates (group)	Glass; glazing on ceramics
Dolomite $CaMg(CO_4)_2$	Filler in plastic and paint; production of magnesium; production of glass and fibreglass
Gypsum $CaSO_4 \times 2H_2O$	Sheeting; plaster; Portland cement
Ilmenite $FeTiO_3$	Pigment in paints (titanium white), filler in plastics
Kaolin $Al_2Si_2O_5(OH)_4$	Pozzolana cements, filler in plastics and paint
Limestone $CaCO_3$	Mortars; plasters; pozzolana cements; Portland cement; lime sandstone;binder in cements; production of glass and fibreglass; paints and lyes; production of steel
Magnesium carbonate $MgCO_3$	Cements
Mica (group)	Production of vermiculite, fireproof glass
Montmorillonite $Al_4Si_8O_{20}(OH)_4 + H_2O$	Waterproofing
Olivin $(Mg, Fe)_2SiO_4$	Filler in plastics, aggregate in concretes
Potassium chloride KCl	Production of glass
Sodium chloride NaCl	Soda; waterglass; production of glass; production of chlorinated plastics
Silicon dioxide SiO_2	Pozzolana cements; production of glass; production of mineral wool; production of silicone
- as fossil meal (diatomite)	Pozzolana; thermal insulation; filler in plastics and paints
- as perlite	Thermal insulation
Sulphur S	Concrete, plasters, production of flame retardants and fungicides
Talc $Mg_3Si_4O_{10}(OH)_2$	Filler in plastics

materials and paints. Asbestos, which was widely used earlier this century, is now more or less completely out of use as a result of its proven health damaging properties.

Generally, the resources of non-metallic minerals are much greater than for metals. Similarly, the energy needed in their production as well as associated pollution is far less. Tables 6.7–6.9, on the other hand, show that use is very widespread; industries such as the glass industry release large amounts of greenhouse gases. One product stands out in particular: the cement industry alone accounts for no less than about 5% of the total global emissions of carbon dioxide (The Cement Sustainability Initiative, 2002).

Extraction of these minerals usually takes place in open quarries, where stones with the lowest impurity content are cut out as blocks, broken down and ground. In a few cases, the minerals can be found as uncompacted material. One important example is quartz sand.

Table 6.6 *Basic materials*

Material	*Main constituents*	*Areas of use*
Hydraulic and non-hydraulic cements	Lime; Quartz; Gypsum; Sulphur; Magnesium oxide; Fossil meal; Ground bricks; Fly ash; Clay; Blast furnace slag; etc.	Structural concrete; concrete flooring, roofing and wall cladding; plasters; mortars; fillers; foamed up as a thermal insulation
Glass	Quartz; Lime; Dolomite; Calcium silicate; Soda; Potash	Openings for daylight in doors and windows; glasswool or foamglass as thermal insulation; external cladding
Sodium water glass	Soda; Silicon dioxide	Additive in cements; flame retardant and insecticide in timber and plant products; silicate paints; adhesives
Potassium water glass	Potash; Silicon dioxide	Silicate paints; adhesives

Extraction involves large quantities of material being moved, causing large scars on the landscape. As with the metallic ores, serious damage can be caused to local ecosystems and ground water that can be quite difficult to restore later. Certain minerals such as lime and magnesium can be extracted by electrolysis from the sea, where the direct environmental impact is somewhat less.

MINERALS FROM THE SEA

Apart from water (H_2O), the main constituents of seawater are the following (in g/kg water): chlorine (Cl) 19.0, sodium (Na) 10.5, sulphate (SO_4) 2.6, magnesium (Mg) 1.3, calcium (Ca) 0.4 and potassium (K) 0.4. Blood has a somewhat similar collection of minerals.

The main material in a snail's shell and in coral is lime. The formation of these structures happens electrolytically by negatively charged organisms, such as snails, precipitating natural lime and magnesium in salt water.

These processes can be performed artificially using electrolysis. The method is effectively the same as that used in galvanizing. A good conductor, usually a metal mesh which can also be used for reinforcement in the structure to be produced, is dropped in the sea and given a negative charge. This is the cathode. A positively charged conductor, an anode, of carbon or graphite is put into the sea close by. As the magnesium and calcium minerals are positively charged from the beginning, they are precipitated on to the metallic mesh. When the coating is thick enough the mesh is retrieved and transported to the building site. The mesh or cathode can have any form and possibilities are infinite.

There are many experiments nowadays around such seawater based industries, even using solar panels as sources of energy. There is evidence that this is an

Table 6.7 *Materials pollution from the production of basic materials from non-metal mineral raw materials*

Material	*Emissions*
Calcined lime	CO_2, SO_2, unspecified dust
Natural gypsum	SO_2
Portland cement	CO_2, SO_2, PAH, NO_x, Tl, Ni, quartz dust, unspecified dust
Glass	SO_2, $CaCl_2$, CO_2, unspecified dust

Table 6.8 *Embodied energy in basic materials from non-metallic mineral raw materials*

Material	*Temperature required in production (°C)*	*Embodied energy (MJ/kg)*
Lime	900–1000	4.5–5.0
Natural gypsum	200	1.2–1.4
Portland cement	1400–1500	3.6–4.0
Geopolymeric cement		3.75
Glass, primary	1400	10.0
Glass, 50% recycled	1200	7.0

environmentally acceptable method for the production of lime-based structures (Ortega,1989).

In the processing of these raw materials, high process temperatures and fossil fuels are often used. Depending on the temperature level there is also a chance that impurities can evaporate into the air, such as the heavy metals nickel, thallium and cadmium. The environment is usually exposed to large amounts of dust of different types.

Many forms of silicon dioxide (SiO_2), have to be seen as risks for the working climate. The main problem is dust from quartz where overexposure can lead to silicosis. The dust can be emitted from several sources such as bricks containing quartz, or the production of stone, cement, concrete, rockwool, glass, glasswool, ceiling paper (where the paper is coated with grains of quartz), paint, plastics and glue. Olivine sand is not dangerous and can be used instead of quartz sand at foundries. Quartz sand can be replaced by materials such as perlite and dolomite as a filling for plastics. Silicon dioxide dusts in the form of fossil meal and perlite are inert compounds and harmless apart from some irritant effect.

When producing cements and lime binders, workers are exposed to many different risks, depending upon the product, such as noise, vibrations and dust that can lead to allergies. Large amounts of the greenhouse gas carbon dioxide and acidifying sulphur dioxide are released. At the construction site workers will be exposed to irritants from dust and from additives in the materials. The form of dermatitis attributed to

Table 6.9 *Process-related and energy-related emissions of carbon dioxide from the production of lime and cements*

Types	*(g CO_2/kg)*
Lime	750
Portland cement	860
Fly ash/Portland cement	670
Blast furnace slag/Portland cement	350
Geopolymeric cement	290

repeated skin contact with chromium ions in Portland cement presents a particular problem. This can be mitigated, as is now often done, by adding small quantities of iron sulphate.

Once in the building these materials are relatively harmless, and as waste they are considered inert. Exceptions to this are asbestos and boron substances which have a pollution risk during their entire lifespan. Gypsum products can also leave sulphuric residues. It should be noted that it is often the various additives to non-metallic mineral products that are problematic in the environment, see Table 6.10 (Andersson, 2002).

The non-metallic minerals are usually impossible or difficult to material recycle as they are usually in the form of new chemical compounds in the final material. Thus, new supplies nearly always have to be extracted. Sulphur though is an exception that can be smelted out easily.

All glass can be recycled by re-melting. Coloured glass can be difficult, and used glass must be cleaned of all impurities first.

6.3.1 The most important non-metallic mineral raw materials for the building industry

Lime is the starting point for the production of pure lime binders, as well as cements. It is also an important ingredient in glass. It is used in the production of iron in blast furnaces, and also in the production of aluminium from nephelin. Here a great deal of lime is used, which becomes Portland cement as a by-product.

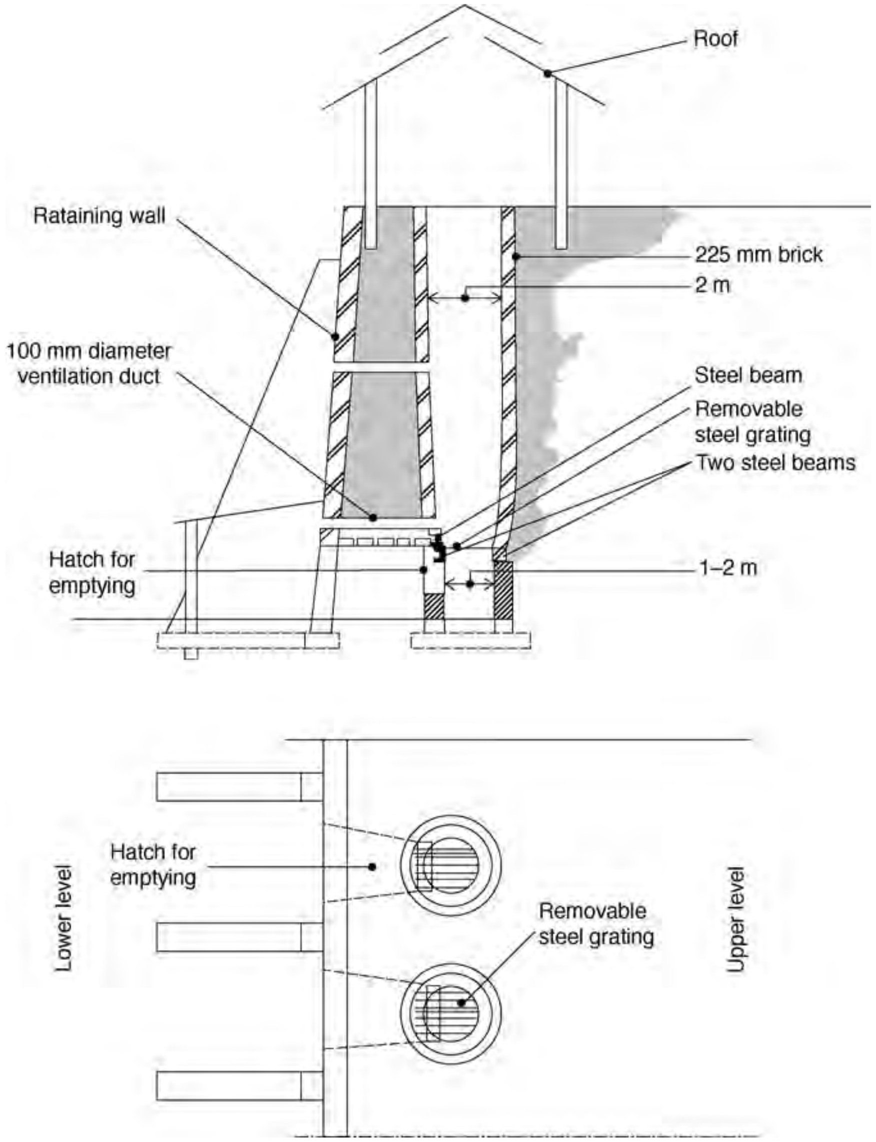
Most places on Earth have deposits of lime, either as chalk deposits or as coral and sand formed from disintegrated seashells. The purity of the lime is the decisive factor as far as the end product is concerned. For pure lime binders there has to be a purity of 90%, preferably over 97%. Lime in Portland cement can be less pure. Chalk is a white or light grey lime originating from the shell of *Foraminifera* organisms.

The production of lime binder from lime ore starts with a combustion process, usually called calcination:

$$\mathrm{CaCO_3 = CaO + CO_2 - 165.8\ kJ} \qquad (1)$$

This dividing reaction is endothermic and continues as long as the temperature is maintained at 800 to 1000 °C. In production of Portland cement a temperature between 1400 and 1500 °C is needed. The above reaction illustrates how carbon dioxide is the inevitable by-product, and the high temperature also means that the process is energy intensive. In the production of Portland cement approximately 50% of the emissions of carbon dioxide is from the chemical process, and 50% from burning fuel.

For calcination there are a number of kiln types. Many are simple both to build and use, and production rates of 30 to 150 tons over 24 hours can be achieved in small local plants (Figure 6.2). There are even mobile units that can be used for very small lime deposits (Figure 6.3). Wood is the best fuel, since the flames are longer and create a more even burning of the limestone than other fuels. Also in the calcination of Portland cement wood chips can be used in large



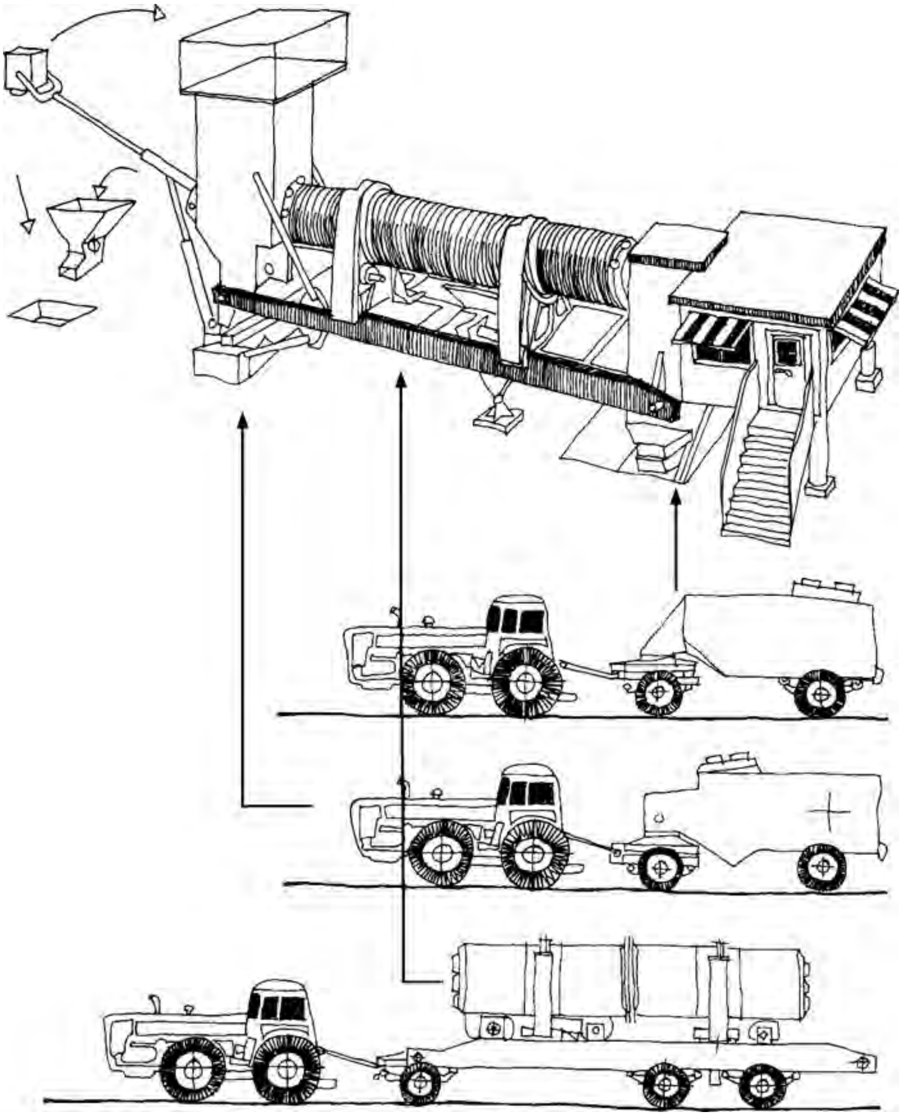
6.2

Local scale calcination plant with shaft kilns.
Source: Ellis, 1974.

quantities, but mineral coal is still the dominating fuel. In the calcination of lime, natural gas and mixed organic waste – such as used car tyres – are also sometimes used. Wood fuel is looked upon as climate neutral whilst the natural gas gives slightly less emissions of carbon dioxide than mineral coal. The emissions from the burning of organic waste depend on the constituents. Plastics and synthetic rubber have emissions similar to fossil fuels.

Calcinated lime can be used directly to make lime sandstone (see Table 13.2) and pozzolana cements. During the production of Portland cement calcination occurs after the necessary extra constituents are added, see page 69.

Lime has to be slaked so that it can be used, without any additives, for renders, mortars and concrete. The slaking process starts by adding water to the lime on a slaking bench. Figure 6.4 shows a very simple



6.3

Mobile calcination plant with rotating kiln.

Source: Spence, 1976.

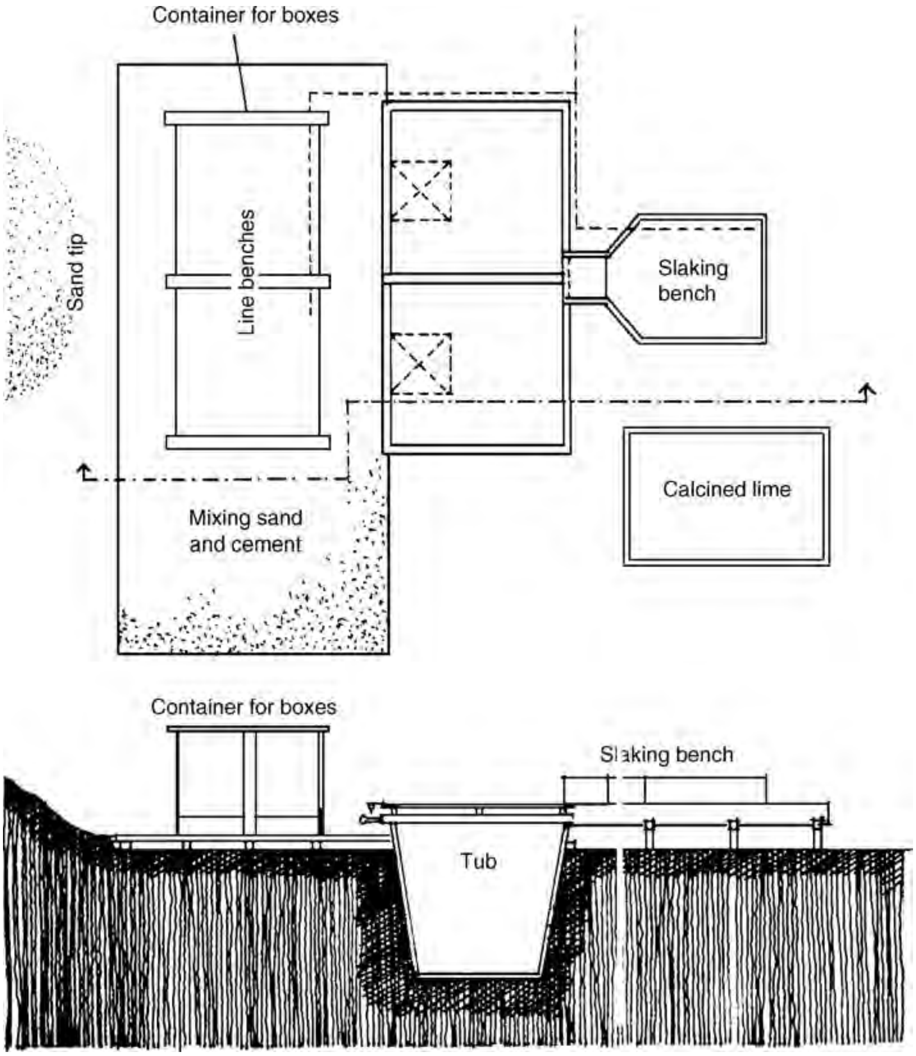
version. The principles are the same regardless of the size of the system. The reaction is exothermic:

$$CaO + H_2O = Ca(OH)_2 + 65.3\ kJ \qquad (2)$$

A part of the energy needed for combustion is now released as heat. The lime swells up quickly and breaks up during a strong 'explosion' of heat. The lime milk is drained into a hollow and covered with sand. The lime is re-slaked and after a week it is usable for mortar, while lime for rendering needs two to three months storage in the hollow.

The lime is supposed to get stronger and harder if the ground moisture performs the slaking process. In that case, storage has to take from three to seven years, anaerobically, at a depth below frost level.

The technique of dry slaking has become more widespread recently. It is an industrial process where the exact amount of water needed is added. The product is called 'hydrated lime'. Whilst ordinary slaked lime is usually mixed with sand and water, hydrated lime is in powder form.



6.4

Small scale production plant for lime mortar.
Source: Jessen, 1980.

This has the advantage of lower transport costs and easier handling on site, where it is mixed with sand. Waste from demolition does not cause any problems. Lime products can, in principle, be material recycled by re-burning.

Dolomite usually has a finer grain than lime but otherwise similar properties. The content of magnesium is too high for use in Portland cement, but it has a certain potential as an alternative to lime in pozzolana cements. The methods for calcination and slaking are approximately the same as for lime.

Gypsum is an aqueous calcium sulphate which is a natural part of stone salt deposits, precipitated in seawater or in lakes. Anhydrite is a white, translucent material that forms gypsum when water is added. Anhydrite and gypsum are used in the production of plasterboard, sheeting, mortars and as constituents in Portland cement. In recent years industrial gypsum by-products have made up a large proportion of the total volume of gypsum produced (see *Industrial gypsum*, page 185).

In order to cast moulds with gypsum, the raw material has to be calcined. A temperature of not more than 160–200°C is needed, which entails relatively low energy consumption. In the process most of the chemically bound water in the gypsum is evaporated and the calcination is complete when the vapour smells like rotten eggs.

Waste from demolition and building sites can develop sulphurous pollution from the breaking down by microbes, but this can be avoided by adding lime to the waste. Waste gypsum can be recycled, but these products are heavy and, therefore, may need much energy in terms of transport.

Silicon dioxide is usually used in the form of quartz sand. It has an important role in several cements and in the production of glass and silicone (polysiloxane).

Silicone is the only common plastic that is not mainly based on carbon. The molecule consists of silicon and oxygen atoms, but needs hydrocarbons and copper to initiate the process which takes place at 400 °C.

Besides quartz there is also usually a high concentration of silicon dioxide in most types of clay. Fossil meal, diatomite, is a type of earth which is rich in silicon dioxide. It consists of petrified and closed shells from silicious algae. Fossil meal is used as pozzolana, or as insulation against very high temperatures, alone or as an ingredient in brick or mortars.

Perlite is a volcanic type of earth with a high content of silicon dioxide and is usually expanded for use in insulation. The largest deposit is situated in Iceland.

Potassium chloride and sodium chloride are extracted from salt water and used to produce the two important base materials *potash* and *soda*, which in turn are the starting point for the manufacture of glass and waterglass.

Potassium waterglass is produced by melting potash and quartz at a temperature of more than 1700 °C. Potash (K_2CO_3) was once produced from the ash of deciduous trees. It is now mainly produced from potassium chloride.

Sodium waterglass is produced by allowing soda to replace potash in a combination with quartz. The soda is made by passing carbon dioxide and ammonia through a concentrated solution of sodium chloride salt.

Chlorine is produced electrolytically from a solution of sodium chloride. It is very important in the production of chlorinated hydrocarbons for the plastics industry. Hydrochloric acid is made industrially by combusting hydrogen and chlorine gas and is used in the production of polyvinyl chloride PVC.

Sulphur occurs in a natural state, as in Iceland, and can be used for casting by melting and then pouring into a mould. Sulphur is also used in the production of ammonium sulphate and aluminium sulphate. Ammonium sulphate is used as a flame retardant and aluminium sulphate as a fungicide in many plant based insulation materials. Sulphur is most relevant to use when it is an industrial by-product (see *Sulphur*, page 185). The natural reserves are very limited.

Mica consists of aluminium silicates and is used as a heat resistant transparent material, for example in the windows of oven doors. Vermiculite is a form of mica that can be expanded by heating to make a granular insulation material. It is mainly used for high temperature insulation. Some deposits of vermiculite have been shown to contain asbestos fibres (US Geological Survey, 2007).

Kaolin is a clay mineral with a high content of silicon dioxide. It is one of the most common minerals and is used as filler in plastics and paints. Metakaolin is obtained from calcination of kaolin clays at temperatures in the range of 700 to 800 °C and is used in lime pozzolana cements.

Montmorillonite is found mainly in bentonite clay. Its most important use is as a waterproofing membrane. By adding water, the clay expands to up to twenty times its own volume. There are many sources on the European continent, but the USA is the main producer.

Phosphates are found in phosphate rock, mainly apatite. Ammonium phosphate which is much used as fire retardant in plant based insulation materials, is produced in a mixture with ammonia which in turn is produced from natural gas.

Borax is extracted mainly from kernite which is relatively common. Boric acid is produced through a reaction with sulphuric acid. Borax and boric acid are used as fungicides and fire retardants in building materials such as insulation made of cellulose fibre, and for timber impregnation. Boron substances are moderately poisonous, and in larger concentrations they affect plants and fish in freshwater.

Asbestos is a fibrous material that was used as reinforcement for ceramics as early as the Stone Age. As a building material it was widely used from around 1935 as reinforcement in different types of concrete, plastic and plaster products, and as insulation, in particular against fire. Use collapsed after the 1960s as it became very clear that asbestos is highly carcinogenic. Products containing asbestos are now banned in most countries.

6.4 NON-METALLIC MINERAL BASIC MATERIALS IN BUILDING

Non-metallic minerals are mainly used in mineral binders and glass.

6.4.1 Cements and limes

Cement is a collective name for mineral binders in powder form, which set to become solid when mixed with water. Pure lime binders are not usually considered cements. The main difference is that lime solidifies when it reacts chemically with air, while cement reacts with water in a hydrating process. It is a hydraulic binder that can also be used under water.

The cement most usually used in building today is Portland cement, but there are many other cements that have been used throughout the ages. The high energy consumption and emissions of carbon dioxide associated with Portland and similar cements based on lime have recently led to experiments with alternatives. In geopolymeric cement, the Portland cement is completely replaced by sodium oxide Na_2O.

Cements in construction have three basic functions: as plaster, mortar and concrete. The consistency depends on the number and size of the constituents, cement, sand, gravel and stone, the proportion of water, and quite often various additives; for example, antifreeze liquids and plasticizers.

HISTORY

The use of calcined lime and gypsum-based materials goes back to approximately 10 000 BC in Mesolithic Palestine (Wright, 2005). Excavation of Neolithic dwellings in Jericho dated back to 8000 BC has revealed an extensive use of concrete as a floor material. This concrete is almost completely made of lime, used as both cast material and filler. The technical quality can be compared with modern concrete as regards its absorption of water and compressive strength, and it is so widespread that there must have been a relatively well-developed production technique using high-temperature kilns (Malinowski *et al.*, 1987).

In Egypt there are solid structures that are 5000 years old and have gypsum as the main constituent in the mortar, whilst Greece used lime mortar. In Mychae on the Greek mainland, exposed lime mortar 3000 years old is still intact. The mortar was made the 'modern' way by mixing burnt and slaked lime with sand in the proportions 1:1 or 1:2.

The Romans mixed finely ground volcanic stone with their lime mortar 2000 years ago. They thereby produced a hydraulic mortar which could withstand both saltwater and freshwater. The volcanic stone was fetched from Pozzuoli, and named *pozzolana*. The Romans later discovered other mineral substances that could be used as ingredients, such as ground bricks and pottery.

The introduction of different pozzolanas revolutionized the building of walls and stronger arches and vaults. The Pantheon in Rome has a cassette vault cast in pozzolana cement. These cements were also used to make baths, water pipes and aqueducts watertight, and as a jointing material between roof tiles.

During the 'Dark Ages' after the fall of the Roman Empire, pozzolana techniques seem to have been forgotten. With very few exceptions, such as the Sophiysky Cathedral in Kiev (1000–1100), builders returned to slaked lime. Certain regions managed with clay; for example, the stone churches of Greenland (1100–1400), but this was rather disappointing for future archaeologists: when the roofs had disintegrated, the rain washed the clay away, leaving only a pile of stones.

During this period, additives to the lime such as oxblood and casein provided watertightness and more elastic mortars. The pozzolana mixture turned up again in England during the sixteenth century. Around 1800 James Parker from Northfleet made 'Roman cement' – a somewhat misguiding nomenclature – by firing crushed argillaceous limestone, which contains small amounts of fossil meal and is found along the banks of the Thames.

In 1824, an Englishman, Aspedin, patented what he called Portland cement, because it resembled rock quarried on the Portland peninsula in the south of England. Within 20 years it had developed into the mixture still in use today. Many more cements similar to Portland cement have been developed since then, in which Portland cement is often an important ingredient. These cements have different expanding, elastic or quick-drying properties.

In northern Europe there are approximately 35 different types of cement on the market. In the industrial countries its use is of the order of 1.7 m^3/year/per person; in countries with low and middle industrialization it is approximately 0.3 m^3.

Apart from problems associated with centralized industry, such as vulnerability to market forces and distance from the user, the cement industry also has high transport costs because of its weight, and extra care is required because of cement's sensitivity to moisture.

An alternative is a cement industry based on medium or small-sized units. Establishing such units takes little time, and investment is small enough to be covered locally. This has been successfully demonstrated in countries like India. These smaller plants can be placed where the cement is to be used and the raw materials extracted**.** The technology is relatively straightforward and can be adequately served by local workshops and services.

Hydraulic binders

Hydraulic binders include lime pozzolana cements, hydraulic lime, Portland cement, Portland pozzolana cements and mixtures of lime and Portland cement.

A hydraulic binder can harden with humidity even under water, but it must contain an acid substance. The most suitable are silicon dioxide and aluminium silicates, which are plentiful in clay. Argillaceous ingredients such as pulverized brick as well as silicium rich substances such as fossil meal and volcanic earth can be used, as well as waste ash from silica plants (see page 178). The hardening reaction is:

$$2(2CaO \times SiO_2) + 4H_2O = 3CaO \times 2SiO_2 \times 3H_2O + Ca(OH)_2 \qquad (3)$$

One might think that quartz sand, which is almost pure silicon dioxide SiO_2, would be usable. However, quartz sand cannot, in principle, form silicic acid under normal pressure and temperature conditions. It can in a damp, warm atmosphere and under pressure – a method used in the manufacture of lime sandstone. In many of the European castles of the Middle Ages a mixture of lime and quartz sand was used as a cold mix; we must assume that the silicic acid has been released from the sand over time, thus forming a durable binder, as these buildings are still solid today.

Pozzolana cements are low energy materials, because pozzolana production requires only moderate heat. For the same reason there is very little gaseous pollution during production. Heavy metals such as nickel and thallium need a much higher temperature before vaporizing. Pozzolana cements can also be produced more economically than Portland cement, but they are often weaker. A ton of Portland cement is equivalent to 1.7 tons of lime pozzolana cement.

The following hydraulic binders are of current interest.

Lime pozzolana cements

Fossil meal/slaked lime. Fossil meal is an earth rich on silicon dioxide SiO_2 that consists of shells of petrified silica algae. Pure fossil meal reacts with slaked lime in its natural state even in weak frost, whilst fossil meal mixed with clay needs to be fired to a temperature of 600 °C to mix with slaked lime. Higher temperatures reduce the reactivity of the lime. Very few experiments have been undertaken with this cement.

Calcined clay/calcined lime. Most clays react with lime after they are calcined. To be used as pozzolana, clay must be calcined to sintering level, which is usually around 550–650 °C. Firing time is about half an hour, but the reactivity and viability of different types of clay varies. All ceramic clays are suitable for pozzolana, especially clays with a high kaolin content (Velosa *et al.*, 2007).

Clay and lime cements are used today in parts of Asia. In India this cement is called 'Surkhi', and consists of lime ground with pulverized brick. It is weaker than Portland cement, but has better waterproof properties and has been used widely in dam building.

Blast furnace slag/calcined lime. The starting point for a reactive blast furnace slag is granulation. The glowing slag is tipped into a vessel filled with cold water. It is then ground into powder and mixed with calcined lime. An alternative is a mixture with dolomite calcined at 800–900 °C, which also works well. The strength of slag and lime cements is good, but the mixture cannot be stored for long periods and must therefore be used shortly after production.

Hydraulic lime

Hydraulic lime is produced from natural limestone containing 6 to 20% clay impurities. Firing is done as for lime. After hydraulic lime is mixed with water, it begins to set in air. It will also eventually set underwater, and can be used for casting underwater in the same way as hydraulic cement. The strength in this concrete is about half to two-thirds that of normal Portland cement.

Portland cement

The main constituent of Portland cement is limestone (65%), which is broken up and ground with quartz sand and clay or just clay. The sulphur content must be below 3%.

In the wet process, water is added during grinding so that it becomes slurry. A dry process has now almost completely replaced the wet process. The dry process is considerably less energy intensive. The mixture is calcined in kilns at 1400–1500 °C and sintered to small pellets called cement clinker.

Vertical shaft kilns or rotating kilns can be used, but the rotating kiln is dominant in the industry. Rotating kilns, at their most efficient, yield 300 to 3000 tons a day; shaft kilns produce 1 to 200 tons a day. Modern shaft kilns have a higher efficiency and certain functional advantages, such as low energy consumption (Spence, 1980).

After firing, the mass is ground again and usually a little finely ground glass or gypsum is added to regulate setting. Pure Portland cement is seldom used today – it is usually mixed with lime or pozzolana.

Portland pozzolana cements

Pozzolanas react with lime in Portland cement, resulting in cements that not only require less production energy but also have higher strength and elasticity. Twenty to Thirty per cent fossil meal may be mixed in. In calcined clay/Portland cement, clay is mixed in, in a proportion of 25–40%.

Industrial pozzolanas can also be used. For the production of blast furnace slag/Portland cement; the slag is granulated and ground with Portland cement in a proportion of 1–85%. So-called Trief-cement consists of 60% slag, 30% Portland cement and 2% cooking salt. It is usually recommended to use far less slag – preferably under 15%. Fly ash/Portland cement has about 30% ground in fly ash. The same proportions are used if mixing with industrial silica dust, *microsilica*. Ground recycled glass is also a potential pozzolana (Pereira *et al.*, 2007). New methods of grinding Portland and pozzolana extra finely together in a vibrating grinder allows the proportion of pozzolana to be increased, for example up to 60% fly ash (Ronin *et al.*, 2004).

Blast furnace slag often slightly increases radioactive radiation from the material. Particles of poisonous beryllium can be emitted from fly ash, and easily soluble sulphates can leach out from waste and pollute the ground water.

Lime Portland cement

Lime Portland cement is made by grinding larger or smaller proportions of slaked lime or hydrated lime into Portland cement. Mixing can also take place on the building site. The mix has a better elasticity than normal Portland cement, both during use and in the completed brickwork.

Portland aplite cement

The intrusive rock aplite consists of quartz and feldspar. Ground aplite powder is highly reactive and can replace more than 70% of the Portland cement in a high quality cement. As a result the emissions of carbon dioxide can be reduced to one third compared to traditional Portland cement. Aplite is abundant and frequent in all areas where granite massifs occur. Concretes made with Portland-aplite cement are assumed to be strong. It was probably first used in the Norwegian coastal town of Ålesund in the early 1900s, and was then more or less forgotten until recently.

Calcium sulfoaluminate cement

Calcium sulfoaluminate is manufactured by heating finely ground aluminium oxide, calcium carbonate and calcium sulphate to around 1000–1100°. Included in clinkers it constitutes a low energy cement compared to conventional Portland cement. Emissions of carbon dioxide are reduced by approximately 50% through lower fuel consumption and lower limestone content. However, emissions of sulphur dioxide SO_2 are usually significantly higher. The use of calcium sulfoaluminate cements has been pioneered in China on a large scale.

Geopolymeric cement

Portland cement contains limestone as well as additions of aluminosilicates such as quartz sand, clay or fly ash. To produce geopolymeric cement the limestone is completely substituted by sodium oxide and processed in a low temperature chemical reaction. Sodium oxide is produced from potassium chloride or sodium chloride in a relatively energy intensive process, but the quantities of raw material required are considerably lower than with limestone. The energy used during production is therefore less, and chemical emissions of carbon dioxide are avoided completely. This cement has somewhat lower pH stability than Portland cement, making the use of steel reinforcing more difficult. It has nevertheless been estimated that around 25% of the

Table 6.10 *Additives in cement and concrete*

Additive	*Contents*
Accelerators	Calcium chloride, calcium formiate, amorphous aluminium hydroxides, aluminium sulphate, triethanolamine, thiocyanate, sodium and potassium waterglass
Adhesion increasing agents	Silicones, synthetic resins such as polyvinyl acetate, acrylics, epoxy, polyurethane, styrene and butiadiene compounds
Aerating agents	Hydrogen peroxide, aluminium powder, magnesium, zinc, maleic acid-anhydride
Air-entraining agents	Natural resins (colophony etc), fatty acids and oils, lignosulphonates, alkylpolyglycolether, alkyl sulphonates and alkylsulphates (e.g. ethylene ether sulphate, sodium dodecyl sulphate, tetradecyl sulphate, cetyl sulphate, oleoyl sulphate, phenol etoxylates, sulphonated naphthalenes), tensides, plastic pellets
Anti-alkali reactive agents	Lithium- and barium salts, pozzolanas
Anti-corrosion agents	Sulphites, nitrites, benzoates
Anti-freezing agents	Alcohol, glycols, inorganic salts
De-foaming agents	Tributyl phosphate, polydimethyl siloxane, alcohols
Chromate reducers	Iron-sulphate, Tin-sulphate
Expanders	Iron powder, sulphur-aluminate cement
Fungicides	Formaldehyde compounds (tetramethylolacetylene, benzylhemiformal), phenolic compounds (p-chlor-m-cresol), isolthiazolinones (methylchloroisothiazoline, methylisolthiazoline, benzisothiazoline, n-octyl-isothiazoline), copper salts, dieldrin
Grouting aids	Aluminium powder
Permeability reducers	Bentonite clay, lime, fossil meal
Recycling aid for wash water and concrete remains	Phosphonic acids (2-phosphonobutane-1,2,4 tricarboxylic acid (PBTC)), fruit acids (citric acid)
Retarders	Sucrose, Gluconates (sodium gluconate), phosphates (tetrapotassium pyrophosphate, sodium tripolyphosphate, sodium hexametaphosphate), borates, silicon fluoride, lead and zinc salts, gypsum
Water reducing agents (plasticizers)	Lignosulphonates, polyhyroxy-carboxyl-acids and salts, polyethylene glycol, melamine formaldehyde sulphonates, naphthalene formaldehyde sulphonates, aliphatic amines, sodium silicate, sodium carbonate, polycarboxylates, nonylphenols
Water repellants	Calcium stearate, stearic acid, oleic acid, fats, butyl stearate, wax emulsions, aluminium stearate, bitumen, silicone, synthetic resins
Water retaining admixtures	Starch derivatives, polysaccharides, polyethylene oxides, polyacrylates, silica dust

Source: Deutche Bauchemie, 2005; Kjær, 1982.

Portland cement used in Europe could be replaced by geopolymeric cement (Kram *et al.*, 2001).

Non-hydraulic binders

Lime

Lime reacts as a binder with carbon dioxide in the air to form a stable compound.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \tag{4}$$

This reaction is exothermic in the same way as slaking, in that the energy used in firing is now released. It takes a long time for the lime to set, and the process is slower at low temperatures.

Gypsum

Calcined gypsum is mixed with water and forms a widely used binder. It is usual to grind the calcined substance with additions of lime or dolomite, which act as catalysts for setting. The calcined gypsum can even be used as *plaster of Paris*. Plaster products are flame retardant since the gypsum calcinates with extreme heat, releasing water.

Additives

Cement is often complemented with additives, either initially or during on site mixing (Table 6.10). The first additives were used as early as 1920. During the 1960s and 1970s the amounts grew. In Denmark there are now additives in 60–70% of all concrete (Strunge *et al.*, 1990). The amounts vary, but the additives seldom form more than 10% of the weight of the cement. Amongst the most important additives are:

- *Accelerators*, which increase the rate of setting, usually sodium silicate (waterglass) 1–3% by weight of the cement. Different amounts of aluminates, carbonates, formiates, thiocyanates can be used as well as triethanolamine in some products.
- *Air-entraining agents*, used to allow a controlled quantity of small, uniformly distributed air bubbles to be incorporated in the mix, thereby increasing the workability and improve frost resistance. Most used are soaps from natural resins, alkylpolyglycolether, alkylsulphates and alkylsulphonates, usually mixed in with 0.05–1% of the weight of the cement.
- *Retarders*, which delay setting during transport in concrete mixer trucks. These contain sucrose, gluconates, phosphates, lignosulphates and typically comprise 2% by the weight of the cement.
- *Water reducing agents* can be up to 5–10% by weight of the cement and reduce the surface tension of water. Admixtures are waterglass, sodium and soda. In industrialized products lignosulphonates, melamine sulphonates, naphtalene sulphonates and polycarboxylates are much used. In some products nonylphenol may be found. These are usually at the same time plasticizers.
- *Water repellents*, which make the substance more waterproof. Calcium stearate is much used, in proportions of 1–5%.

Cement production and energy use

Energy consumption in production varies widely according to the type. Portland cement has a relatively high energy consumption, largely due to the high temperatures needed for production (up to 2000 °C in the firing zone). The cement industry is usually very centralized and the use of energy for transport is thus also high.

It would be a significant achievement to reduce energy consumption in both production and transport. Decentralizing of cement production could save a great deal of energy, not only in transport, but also because smaller plants can be as efficient as larger plants. Today rotary kilns are used, but smaller, more efficient, modern shaft kilns could reduce energy consumption by 10–40%. Rotary kilns are very specialized – shaft kilns have a greater variety of possibilities. They can be used for both calcination and sintering of most cement materials.

In the last decades, the pre-calcination technology has been introduced as an energy saving measure. Another energy saving measure is an increased number of pre-heaters in the cement factories. There are also many ways of utilizing the waste heat; for example, as district heating.

Another step in the right direction is developing cements where lower temperatures are required in the production process. Most important here are the geopolymeric cements and cements with high amounts of pozzolanas mixed in. Also increased use of limestone powder ground directly into the clinker has a positive effect on the energy demand (Jahren, 2003).

Cement products and pollution

To produce Portland cement in rotary kilns requires energy sources such as coal, crude oil or natural gas. Emissions and pollution is therefore the same as for other uses of fossil fuels, including high emissions of the greenhouse gas carbon dioxide. The temperature in the firing zones is so high that nitrogen oxides are also emitted. This is not removed from the effluent today, though the technologies exist; for example, *catalytic reduction*. Shaft kilns can in principle be fired with wood, which is considered as climate neutral.

The raw materials used in cements and limes also emit large amounts of carbon dioxide and sulphur dioxide. The extremely high temperatures used in the production of Portland cement also suggest that heavy metals are emitted. Sulphur dioxide can, in principle, be cleaned by adding lime to the flue gases.

Part of the carbon dioxide emitted will be slowly reabsorbed in a process called carbonatation. This is greatest for the pure lime products (Fossdal, 2006). The process is:

$$\mathrm{CaO} + \mathrm{CO_2} \rightarrow \mathrm{CaCO_3} \qquad (5)$$

Carbonatation can in theory be up to 90% of the carbon dioxide chemically emitted from the calcination over a 50-year period in the case of an exposed lime plaster – which also leads to an increase in weight of around one kilogram per square metre. For Portland cement based plasters carbonatation can attain up to 70%; a lower figure partly because the material is less porous, and part of the calcium compounds are retained within the silicious constituents. For thicker, typical concrete constructions, carbonatation is unlikely to surpass 10 to 15% in practice. Carbonatation will continue after demolition of cement-based structures, and will be more rapid if these are broken up into small pieces and exposed to the air.

Methods are being investigated to add carbon dioxide during the setting process. The most effective step towards reducing the climate impact of cements however lies in the increased use of pozzolana mixtures in both hydraulic lime and Portland cements. In this way the amount of lime can be reduced. Here the use of aplite cement and calcium sulfoaluminate cement are also interesting options. Geopolymeric cements for uses requiring somewhat lower strength could also lead to significant reductions.

The problem of dust has previously received much attention in connection with cement production. Today the dust problem is often much reduced as a result of better, closed systems for handling clinker, more efficient dust filters, etc.

Dust can still be a major problem on building sites and wet Portland cement can cause skin allergies. During the construction phase itself, cement products are relatively free of problems, though if setting is not effective chemical reactions can occur between it and neighbouring materials, such as PVC floor coverings.

At the stage of waste, cements are relatively inert as long as they are free of additives. There is not yet much knowledge as to the behaviour or leakage into the environment of typical concrete additives once deposited as waste. Sulphur compounds can however be leached out from gypsum-based products.

6.4.2 Glass

Transparent surfaces provides views, light and solar warmth. However, like the rest of a building envelope, they must protect against rain, cold, heat and noise. Few materials can satisfy these different demands at the same time. There have been many alternatives throughout history: shell, horn, parchment, alabaster, oiled textiles, gypsum (selenite) and thin sheets of marble. Eskimos have used the skin of intestines. In Siberia mica is cut into sheets for windows, known as Russian glass.

None of these seriously rival glass, and the only alternatives commonly in use are rice paper, used in Japan for letting light pass from room to room internally; and more recently, plastic alternatives, such as the polycarbonate sheet much used in greenhouses.

Ordinary clear glass lets about 85 to 90% of daylight pass through. There are many other types of glass on the market: diffuse, coloured, metal-coated, reinforced, heat reflecting, etc. Glass has also been developed to perform other functions, such as insulation blocks (foam glass) and as fibres in glass wool, the latter having a very large proportion of the insulation market nowadays.

HISTORY

The Phoenicians were probably the first to produce glass, about 7000 years ago. The oldest known piece of glass is a blue amulet from Egypt. Glass painting began in the eighteenth Pharaonic dynasty (1580–1350 BC), but it is difficult to say if glass windows were produced during this period.

A broken window measuring 70 by 100 cm and 1.7 mm thick, opaque and probably cast in a mould, was excavated from the ruins of Pompeii. It was originally mounted in a bronze frame in a public bath.

Plate glass technology spread slowly through Europe. Glass craftsmen kept their knowledge secret, and only the Church, with a few exceptions, was allowed to share the secrets. Early glass was blue-green or brown, partly because ferrous sand was used as a raw material. Later it was discovered that adding magnesium oxide (glassblowers' soap), neutralized the effect.

During the eighteenth century glass became affordable for use in all houses. It was still expensive, and far into the nineteenth century it was normal to put many small pieces together to make one larger pane. From 1840 methods of plate glass production improved and glass became cheaper. The methods of production were still basically manual – glass spheres were blown then divided.

In Belgium in 1907 the first glass was produced by machine. In 1959, float glass was developed, for the first time giving a completely homogeneous surface without irregularities.

Different proportions of raw materials can be used to make glass, but it usually consists of 15% soda ash (sodium carbonate), 15% limestone and dolomite and 70% silicon dioxide in the form of quartz sand. The formula for the process is:

$$Na_2\,CO_3 + CaCO_3 + SiO_2 = Na_2O \times CaO \times 6SiO_2 + CO_2 \qquad (6)$$

This glass, based on soda ash, is the most common. Replacing the soda ash with potash (K_2CO_3) gives a slightly harder glass. Lead glass is achieved by replacing limestone in the potash glass with lead (Pb).

For glass that needs high translucency for ultraviolet light an important constituent is phosphorous pentoxide (P_2O_5).

Fluorine compound agents decrease the viscosity and melting point of glass mixtures, which can reduce the use of energy. Antimony trioxide (Sb_3O_2) can be added to improve malleability, and arsenic trioxide (As_2O_3) acts as an oxidizing agent to remove air bubbles from the molten glass. Both are added in a proportion of about 1%. Stabilizers that increase the chemical resistance are often used: CaO, MgO, Al_2O_3, PbO, BaO, ZnO and TiO_2.

Coloured glass contains substances that include metal oxides of tin, gold, iron, chrome, copper, cobalt, nickel and cadmium. Traditionally, coloured glass has been used for decoration. In modern coloured glass the colouring is very sparse and it can be difficult to differentiate from normal glass. Decorative qualities are here less important than the ability of the coloured glass sheet to absorb and/or reflect light and warmth. The aim is to reduce the overheating of rooms or, conversely, reduce heat loss. Products that achieve this are usually known as *energy glass*, and have a high energy saving potential.

There are two types: ‘absorption glass’, which is coloured or laminated with coloured film, and ‘reflective glass’, which has a metal or metallic oxide applied to it in the form of vapour. Early types of energy glass reduced the amount of light entering the building by up to 70%; these days, they are much more translucent, but the area of glass in a room may still need to be increased to achieve adequate levels of light.

Production of glass for windows

To produce good glass, good quality raw materials with no impurities must be used. The ingredients are ground to a fine powder, mixed and melted.

Melting

As early as the Middle Ages, glass-works used ‘pot kilns’. The method is comparable to ordinary cooking. The pot is heated by a fire or gas flame. Dry glass mix is poured into the pot and heated to 1400–1500 °C. Recycled glass only needs 1200 °C. When the mass has become even and clear, the temperature is lowered, and the substance removed in small portions and cast into a mould. In theory, the glass is soft and can be worked until the temperature falls to around 650 °C. The usual working temperature in the production of windows is about 1000–1200 °C. The capacity of a pot kiln is about half a ton per day. They are still used in smaller glassblowing workshops for glass artefacts, but not in the production of windows.

In industrial methods, closed tanks with an inbuilt oil burner or electrical element are used. Typical tanks are made of fireproof stone and have a capacity of 200 to 300 tons per day. The working temperature is the same as that of the pot kiln. A tank kiln will run at full capacity continuously and may only last two to three years. The glass produced can be shaped using a series of different techniques.

Casting

Casting, most likely the first method for glass plate production, works on the simple principle that the melted glass mass is poured into smooth moulds and then rolled out. This technique is still used for some types of glass where translucency is less important, such as decorative, profiled and wired glass. Glass bricks are made from two half blocks later fixed together.

Crown glass

Crown glass was the most usual method up to about 1840. Figure 6.5 shows the production process. The glass is blown into a bubble, a rod is stuck to the sphere, and the blowpipe then removed. The pin is spun while the glass is heated and the glass bubble opens up, becoming a circular disc up to 1 m in diameter, which can then be cut into panes. The pane in the middle – the bottle glass – is the lowest grade**.** These panes with a characteristic circle can still be seen in some old windows**.** Crown glass has low optical quality, with bubbles, stripes and uneven

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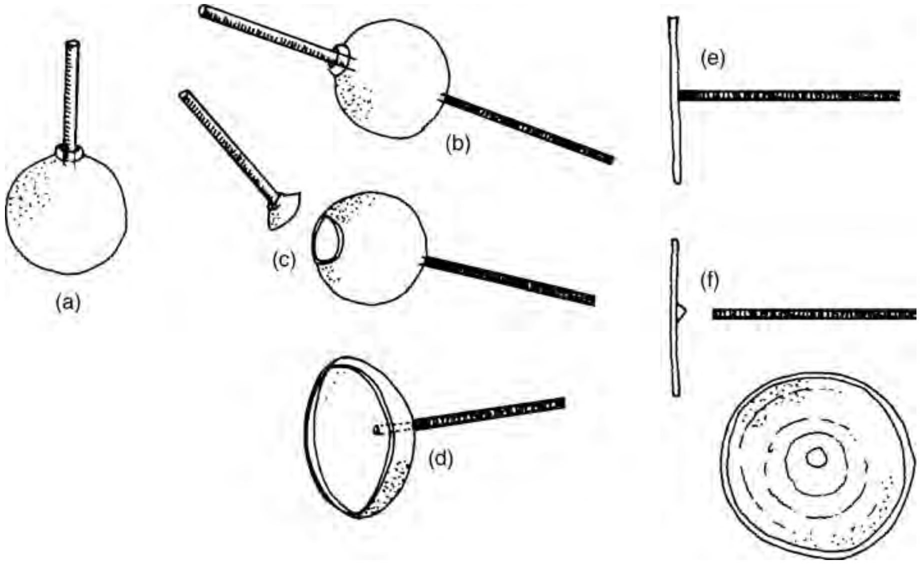


6.5

The production of crown glass: (a) the glass is blown into a bubble; (b) an iron rod is fixed to the glass bubble; (c) the blowpipe is removed; (d) the glass bubble opens up after being warmed and rotated; (e) when completely open, the bubble becomes a flat, circular pane of glass; (f) the iron rod is removed. The pane of glass has a thick edge and centre, but is otherwise clear.

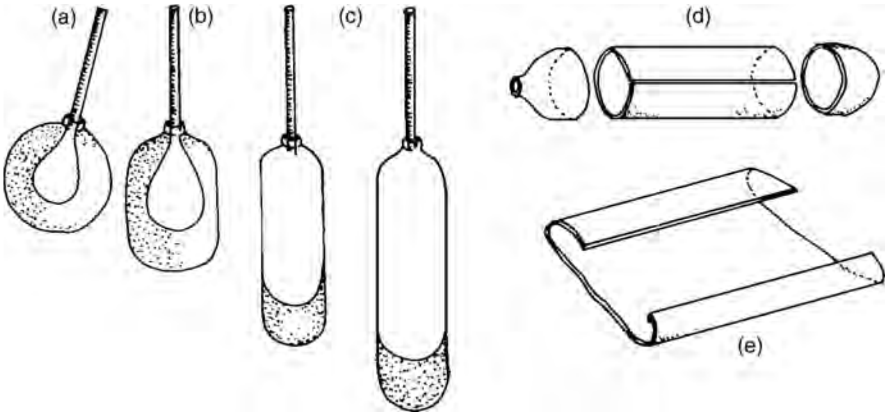
thickness. Today it is only used as decoration, or in panes where translucency is not required.

Table glass

Figure 6.6 shows the production process for table glass. Here, the glass mass is blown into an evenly thick cylinder in a mould 2–2.5 m long and 60 cm in diameter. After blowing, the end pieces are removed and the cylinder is opened. The glass is then heated and stretched into a flat sheet. Table glass has a much better optical quality than crown glass. With this method, larger panes of glass could be produced.

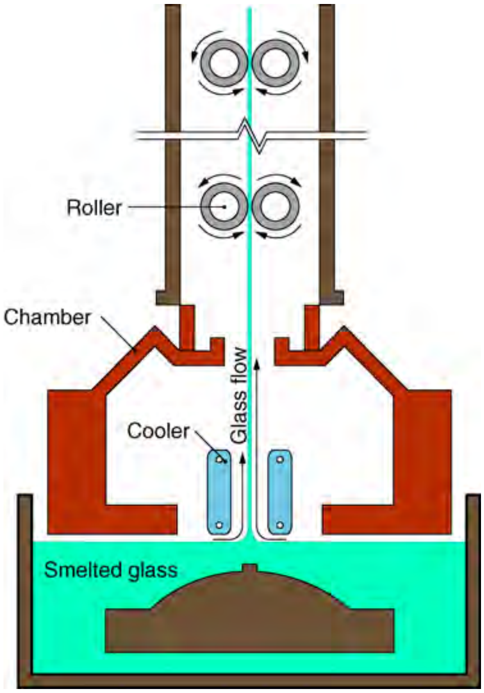
Machine glass

Figure 6.7 shows the production process for machine glass. The glass mass is cooled to 950 °C to become a little tougher. It is then drawn



6.6

The production of table glass: (a-c) the glass is blown within a mould into a cylinder; (d) the end pieces are cut off; (e) the cylinder is opened and divided into the required sizes.



6.7

The principles of production of machine glass.
Source: Saten, 1980.

through a flat nozzle out of the kiln and vertically up between a set of asbestos rolls in a cooling shaft about 12 m long. Reaching the end of this shaft, the glass is cut into the required lengths and slowly cooled.

Float glass

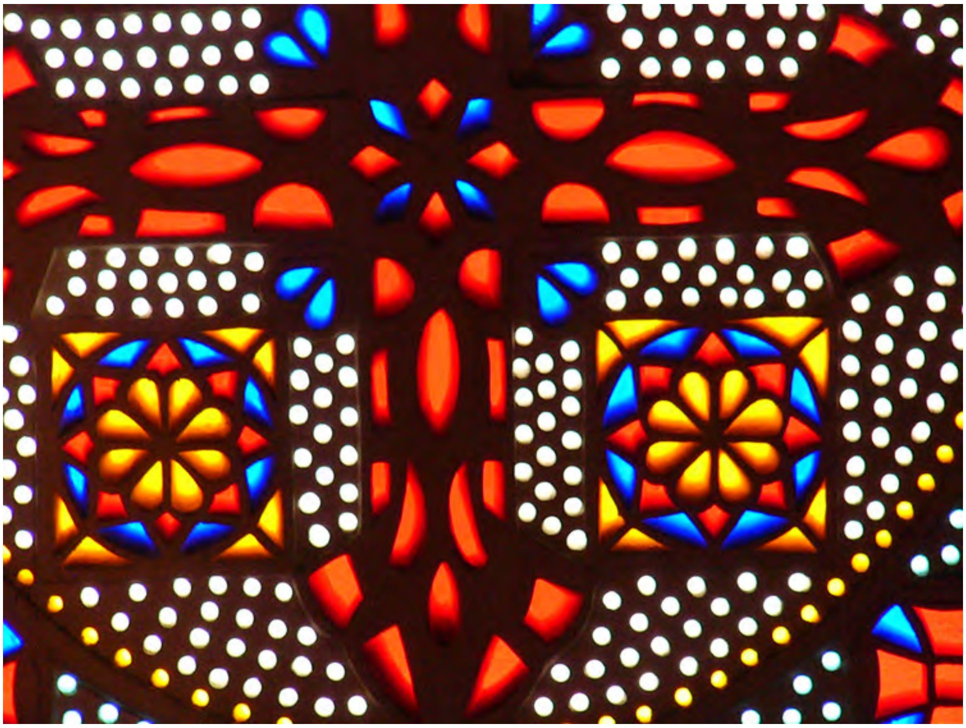
Instead of drawing the glass substance upwards vertically it is poured out over a bath of floating tin. This produces a totally flat sheet that is cut and cooled. This is the method used by most glass manufacturers today.

Ecological aspects of glass production

The reserves of raw material for glass production are rich, even if deposits of quartz sand are regionally limited. Accessible reserves of the metallic oxides necessary for colouring or covering energy glass – most often tin and gold – are generally very limited. The most important environmental factors are the high energy consumption in production, plus the energy related pollution. Material pollution from quartz dust and calcium chloride can occur. When tin oxide is applied as vapour, hydrogen chloride and hydrogen fluoride are emitted, in addition to tin pollution. Gold film emits less pollution than tin.

Glass does not produce pollution in use, but both antimony trioxide and arsenic trioxide can seep out after disposal, causing environmental pollution. Coloured glass and metal-coated glass may contain heavy metal pigments that can be washed out, and need controlled disposal.

Clear glass is well suited for recycling. The production of new glass can in principle use up to 50% recycled glass. Recycled glass can also be used in the production of glasswool and foam glass. Laminated glass and glass covered with metal film cannot be recycled as window



6.8

From the Coptic church in Cairo. Coloured glass is made by adding metal oxides to the molten glass; gold for red, cobalt for blue and copper oxides for green.

glass. All types of glass can however be ground and used as filler in elastomeric roof coverings and in the manufacture of bricks and tiles, as well as for high quality aggregate in asphalts and concretes. Because of a high content of silicon dioxide glass can probably also be used as pozzolana in cements.

Production of glass has become sophisticated and technology dependent, and requires high investment. It is difficult to imagine that a small plant for local production of perhaps one ton per day could be competitive in both price and quality. For glass with a lower standard of translucency and clarity it should be possible to set up local production based on casting recycled glass.

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7 Stone

Many myths compare stones as the ‘bones’ of Mother Earth. Extraction of minerals in most cultures has been accompanied by complex rituals and rites, undertaken as carefully as possible by, amongst other things, filling up the holes and passages into the mine when extraction was finished. A Sioux Indian smallholder expressed this spiritual attitude thus:

> You ask me to dig in the earth. Do I have to take a knife and plunge it into my Mother’s breast? You say that I must dig and take away the stones. Do I have to remove her flesh to reach down to her bones?

There are three main categories of stone:

- *Igneous rocks.* Consolidated areas of rock that have forced their way up through splits in the crust of the earth, these are the hardest types of rock, such as the granites, syenites and dolerites.
- *Sedimentary rocks.* Petrified and disintegrated stone which has combined with organic materials. In this group are sandstone, slate and limestone.
- *Metamorphic rocks.* Formed by exertion of pressure and the action of high temperatures on igneous or sedimentary rock types, which transforms their structure. Examples of these rock types are crystalline slate and quartzite.

None of these groups can be referred to as the oldest, since the geological processes are a continuous, cyclic process. Sedimentary rock types can be formed through hardening of gravel, sand and clay originating from the disintegration or breaking down of igneous or metamorphic rocks; igneous stones can arise through the melting of metamorphic and other types of rock and later consolidation, and metamorphic rocks can arise from changes in older sedimentary, igneous or metamorphic structures.

There may be some truth in the view expressed by Asher Shadmon of the HABITAT centre in Nairobi:

> Stone is the building material of the future. We are on our way into a new Stone Age. The resources are limitless and evenly spread over the whole globe. Extraction does not require a lot of energy and does not pollute. And most important of all is that the material is durable.
> (Shadmon, 1983)

A differentiation is usually made between field stone and quarry stone. While field stone is found in the open, on beaches or in fields, quarry

Table 7.1 *Uses of stone in the building industry*

Type of stone	*Minerals*	*Areas of use*
Clay slate	Clay minerals	Roof covering; flooring
Diabase	Plagioclase; Pyroxene	Rockwool; crushed as aggregate in concretes; structures
Gabbro	Feldspar; Pyroxene	Crushed as aggregate in concretes; structures; flooring; wall cladding
Gneiss	Aluminium silicates; Quartz; Mica	Crushed as aggregate in concretes; structures; flooring; wall cladding
Granite	Feldspar; Quartz; Mica	Crushed as aggregate in concretes; structures; flooring; wall cladding
Limestone	Lime	Ground to limeflour (cement, lime binder, etc.); smaller structures
Marble	Lime/dolomite	Structures above ground; flooring; cladding
Mica slate	Quartz; Feldspar; Mica	Roof covering; wall cladding; flooring
Phyllite slate	Quartz; Feldpar; Mica	Roof covering; wall cladding; flooring
Sandstone/quartzite	Quartz, often incl. lime or feldspar	As sand (production of Portland cement, concretes, fillers); smaller structures
Serpentine	Serpentine minerals; Chlorite; Magnesite	Cladding; flooring
Steatite/soapstone	Talc; Chlorite; Magnesite	Structures above ground; cladding
Syenite	Aluminium silicates; Pyroxene	Crushed as aggregate in concretes; structures; flooring; wall cladding
Quartzite slate	Quartz; Aluminium silicates; Mica	Roof covering; wall cladding; flooring

stones are deliberately quarried. Stone is primarily used in the form of blocks, cut slabs or sheets, as slate or crushed stone (see Table 7.1). It is used to construct walls, retaining walls, edging and bridges. In arch structures or small spans it has been used since antiquity as structural roof material. Dressed stone and specially made slabs can be used for exterior or interior cladding, framing around doors and windows, fireplaces, floors and stairs. Slate can be used on floors, stairs, fireplaces, as framing around doors and windows, as roof covering and as wall cladding. Crushed stone or gravel is used as aggregate in all concrete structures.

Stone has very high compressive strength and low tensile strength. Consequently, it is possible to build high buildings of solid stone, whereas a stone beam has a very limited bearing capacity. The Egyptian and Greek temples show this very clearly: dimensions of horizontal stone slabs are immense to achieve small spans. In Roman aqueducts as in Gothic cathedrals, the principle is that of the arch; the compressive strength is thereby used at its maximum, making spans of up to 70 m possible.

Evidence remains from Upper Palaeolithic times (40000–10000 years ago) of the use of stone for curbs and low boundary walls (Wright, 2005). From earliest Neolithic times field stones have been used for mud mortar as an alternative to mud brick. Around 3000 BC, man began to quarry blocks from bedrock and dress them into regular forms. Some of these beginnings can be seen in Mesopotamia, but it was in early dynastic Egypt that the essential developments took place. Since then, stone has been used continuously, with its apotheosis during the late Middle Ages when a widespread stone industry developed throughout northern Europe. The stone villages of this period were usually built with a foundation wall and ground floor in stone; the rest of the building was in brick. By the early 1900s, the stone industry had lost its status, mainly due to a rapid rise in the use of concrete. Large quantities of stone are still quarried and sawn into slabs, including marble, in countries like Italy and China, and a reasonable amount of slate extraction still continues; but the dominant use for stone today is crushed stone for concrete aggregate.

Many in the building industry anticipate a renaissance in stone building, even if not quite as optimistically as Asher Shadmon. New technologies have made it possible to re-open disused quarries, and use for façade cladding is increasing. One reason is that natural stone – with the exception of sandstone and limestone – is less sensitive to pollution than concrete and related materials. However, all porous stones are exposed to frost damage. In northern Europe frost damage is expected to double with climate change (Noah's Ark, 2006).

Stone is ubiquitous, even if in short supply in certain regions. Extraction and refining is labour-intensive, consequently the use of energy is much lower than for bricks or concrete (see Table 7.2). Stone is, therefore, not responsible for significant energy related pollution.

Extraction and stone crushing is usually a mechanical process with no need for high temperatures. Various energy sources can be used, ranging from manual power to wind and water power, either directly or as electricity-based technology. It is also estimated that considerable energy savings are possible in many stone industries (Konstantopoulou *et al.*, 2004).

The weight of stone suggests that the distance between quarry and building site should be short. Quarries along the coast have the potential advantage of energy effective water transport. Mobile extraction plants could be moved to small quarries near relevant building sites, employing local labourers.

Large quarries inevitably damage the landscape even if they are eventually restored or become overgrown. They can also lead to altered groundwater conditions and damage local ecosystems. To extract granite for use as crushed stone by the 'gloryhole' method, the

Table 7.2 ***Embodied energy in natural stone products***

Products	*Embodied energy (MJ/kg)*
Granite, as blocks	0.5
Granite, as crushed stone	0.4
Limestone, as block	0.5
Sandstone, as block	0.5
Slate	Less than 0.5*
Ornamental stone, different types	1.5

* There are no relevant figures for slate, but we can assume that the embodied energy is lower than for other stones.

Table 7.3 *Potential material pollution during the working of stone*

Final product	*Potential pollution*
Granite/sandstone/phyllite slate/quartzite slate/gneiss	Dust containing quartz
Diabase/gabbro/syenite/marble/limestone/soapstone/serpentine/clay slate	Dust containing no quartz

mountain or rock is drilled from the top and stones extracted through a vertical tunnel (which gets wider the deeper it goes). This leads to less visual disturbance of the landscape.

Stone often contains radioactive elements such as thorium and radium, and a quarry can increase the general level of radiation in a neighbourhood by emitting radon gas. Generally, the extraction of slate, limestone, marble and sandstone has little likelihood of causing radiation risks. Extracting volcanic or alum slate requires caution, including the measurement of radiation levels before removing stone for general use.

Environmental hazards of the industry include noise, vibration and dust. Quartz dust is the most harmful (see Table 7.3). While sandstone usually has a high content of quartz, the content in granite can vary widely from a few per cent to over 50%. More processing leads to greater damage; by using undressed stone rather than perfectly dimensioned blocks, these problems are reduced.

Unless radioactive stone is used in construction, there are no problems during the lifetime of stone in or on buildings, and demolition waste will also be inert.

Quarrying and dressing stone products result in large amounts of waste stone. This can be crushed to make useful aggregate; for example, for concrete.Waste chips from marble quarries are a valued ingredient for terrazzo flooring, and marble dust is useful in the production of lime and cements.

It is useful to reflect on the fact that resource use and waste is partly a question of design. For example, simple decisions such as choosing a floor pattern that can use small sizes of stone of varying lengths, rather than large pieces, will result in half as much waste at the quarry.

The lifespan of blocks, slabs and slates is generally higher than a building's lifespan and components assembled without mortar are especially well-suited for extensive re-use. These secondhand products are usually valuable. Crushed stone also has the potential for recycling as aggregate in concrete products.

7.1 PRODUCTION OF BUILDING STONE

Stone from fields and beaches lay freely scattered in nature. Throughout the centuries these stones have been used and carefully stored. In Denmark, as recently as the twentieth century, round beach stone was so highly valued that several parts of the coast have been totally emptied. This round stone is particularly suitable for building in or near water, especially for piers. But the possibilities are still relatively limited, since cement has difficulty bonding to smooth stone surfaces (Figure 7.1). For larger buildings these loose stones have usually been cut into rectangular blocks for ease of handling.

Quarry stone has been extracted since the early Middle Ages. The work has been by pure muscle power, chisels, sledgehammers and pickaxes. This method was used well into the twentieth century. The stone quarryman's work is one of the least modernized, despite the introduction of explosives and saws, flame cutting tools and other cutting machinery. Traditionally, stone quarrying has always been based on simple and labour-intensive technology, which couldn't compete with growing industrialization. However, in many countries with low and medium industrialization, stone can cost as little as a quarter of the price of concrete. In highly industrialized countries there are signs of improved competition as part of an aesthetic and qualitative trend. A significant factor that will strengthen the case for using local stone is that, in conventional concrete production the amount of energy used comprises 25–70% of the price of the product, and is likely to increase.

7.1.1 Extraction methods

Extraction methods for various types of stone vary slightly, but the main principles are as follows.

Reconnaissance. The rock is inspected and samples are taken and tested for damp absorption, strength, etc. It is important to split the rock without cracking it or causing it to crumble or disintegrate. Layered and slate-like rock is the least problematic, but the distance between splits should not be too small. Rock of the same structure is often evaluated by the sound it makes when hit with a hammer, and by the splinters or angular forms that split off.

7.1

(A) Field stones. (B) Quarry stones. (C) Cut stones.

7.1
(Continued)

Stone need to go through two further tests: for water absorption and heat resistance. The water test involves leaving the stone in water for several days and checking that it does not increase in weight. To test heat resistance the rock is placed in glowing coals and must retain its form and structure when raked out afterwards. A good roof slate passes both tests. Another condition is that a white surface film should not form when exposed to air and moisture.

Quarrying. The surface of a rock is cleared of trees, loose stones, earth and all other organic matter. Holes are drilled for charges. Placement of these is determined by the thickness of the block and the layer formation. The depth of the hole is also important. A 'rimmer' is knocked into the hole. This makes ruts in the wall of the hole along which the block will crack. The hole is then filled with gunpowder, rather than dynamite. Gunpowder has a lower rate of burning and gives a more muted explosion. Dynamite causes microscopic hairline cracks in the blocks that decrease their strength, although for crushed stone this is of no consequence.

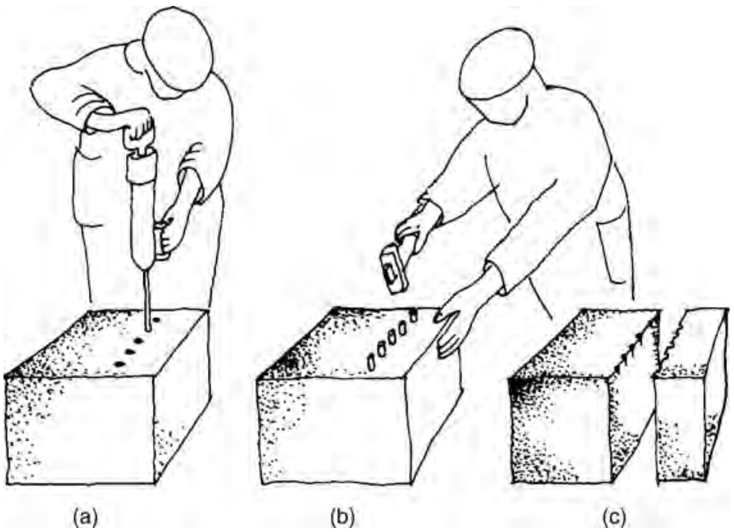
Soft stones such as marble, limestone and soapstone can, in many cases, be removed with a wire saw. This consists of a long line of diamonds that cut 20–40 cm per hour. For rock rich in quartz, such as granite, a jet flame can be used. The equipment for this is a nozzle mounted on a pipe with paraffin or diesel under pressure. The temperature of the flame is about 2400 °C, and the speed is high. A jet flame can cut out about 1–1.5 m^3 of stone blocks per hour.

7.1.2 Dividing and cutting blocks

Stone is seldom used as an unfinished rough block. It is usually divided into smaller units. This can be done in several ways.

Wedging is shown in Figure 7.2. The alignment of the wedges happens in three stages. It requires skill, good knowledge of the nature of the stone and the direction of its layering, and much work.

Guillotining is possible for smaller blocks with clear layering. This splits the stone with one blow and is the most labour and energy-saving



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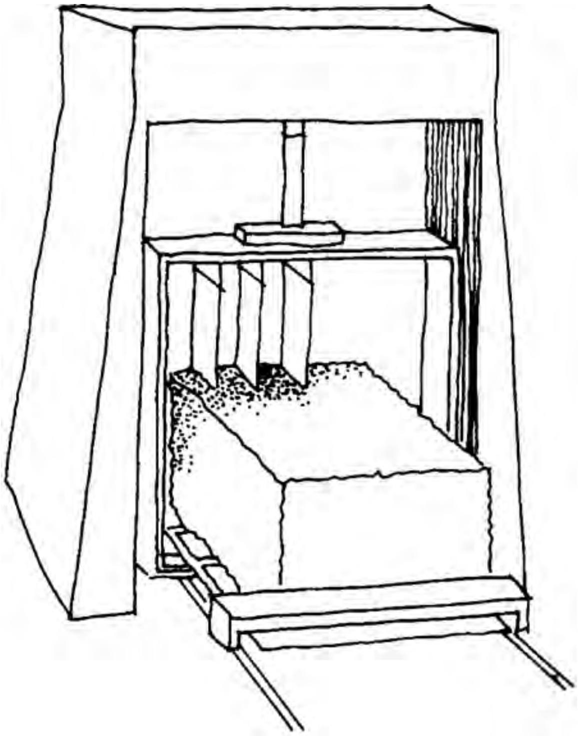


7.3

technique. It is also the principle upon which modern equipment research and development bases its work. Some methods create an artificial tension within the rock with the help of a strong vice. Fractures then occur, which spread out when the axe falls, and in a single moment maximize the tension in one direction. The maximum size available for a rough block, using modern equipment, is up to 250 × 50 cm, depending upon the type of stone. Smaller splitting machines can be carried by two people; and can split stone up to 10 cm thick and also work on loose stone.

Sawing is a common method for dividing blocks. A circular saw or frame saw, preferably with a diamond blade, is used. The frame saw is often used for the production of external façade panels (Figure 7.3). The capacity of a frame saw on hard stone is approximately 30 cm per hour. Circular saws are used for all types of stone and cut considerably faster.

Jet flame can be used on quartz stone.

Waterjet techniques have been developed for cutting stone, using a thin spray of water at an extremely high flow speed which cuts stone like butter.

The finishing process. Further processing is determined by how the stone is to be used. For structural use and foundations stone does not need much working – the surface can be evened out with a hammer. For cladding panels, tiles, etc. the stone requires planing, grinding and polishing.

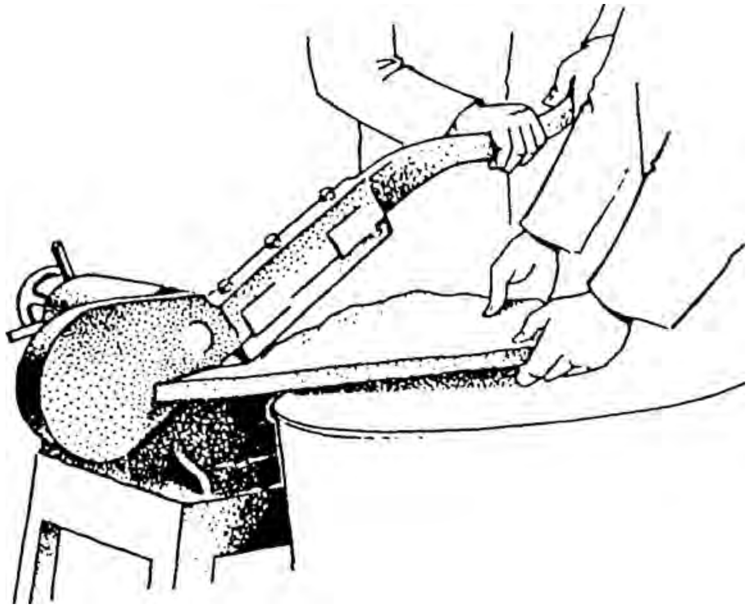
7.1.3 Sorting and cutting slate

Every slate quarry has its own characteristics as regards accessibility, the angle of layers, and splitting. In particularly favourable locations the layers are separated by a thin fatty layer, which makes extraction very simple. In the traditional method, splitting is carried out directly on the exposed shelves within the quarry. In industrial extraction larger pieces are split with a hydraulic hammer and then transported for further splitting.

The secondary working of slate is usually carried out close to its place of extraction. Even at this stage, each slate has its own characteristics and requires its own particular working methods. Slate is typically a material that requires manual labour; machines are not very useful for processing it.

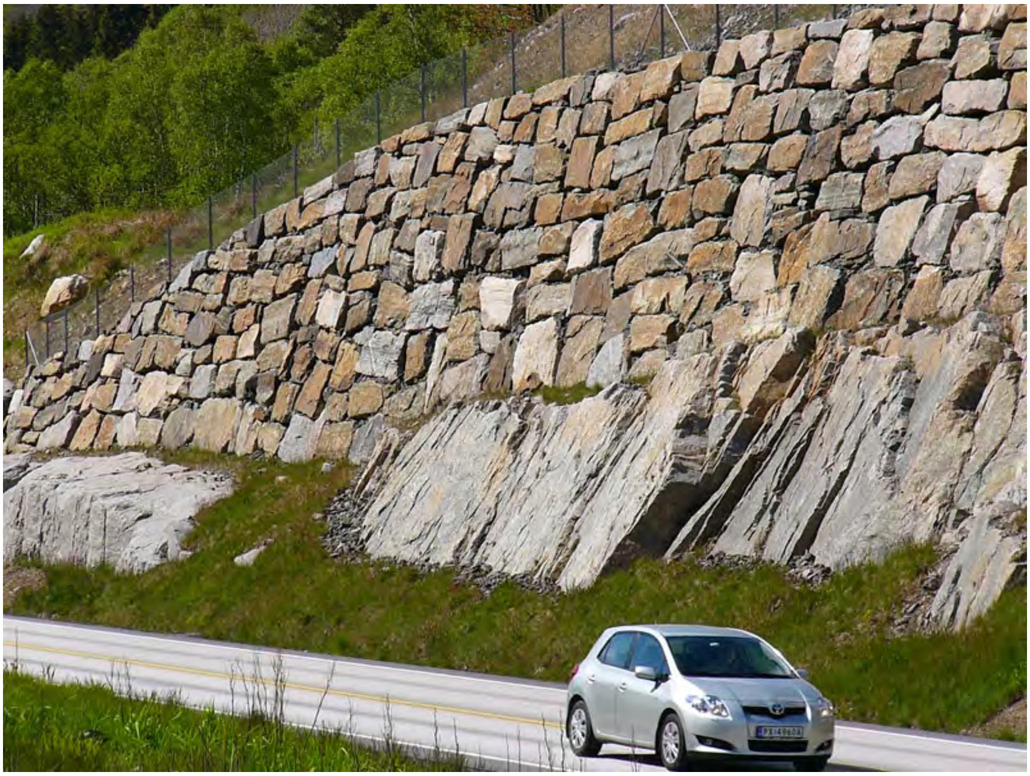
Generally slates should be no thinner than 6 mm, although this varies with type. Thin slates are easily broken during transport. Once laid on either a floor or a roof, slates will not support high impacts.

If slate is struck in the direction of its layers, straight or curved, the structure of the stone is crushed to a certain depth inwards and the stone divides itself. Pouring water over the slate makes the job easier. During one working day a craftsman with a hammer could produce 60 to 80 slates. With the introduction of slate 'scissors' (see Figure 7.4) which has dominated production since the turn of the nineteenth century, the number went up to 400 slates a day. A small wooden block is used to position notches for the fixing nails, which are knocked out with a pick hammer or cut out with an angle grinder. The working bench is a trestle with slate lying on it. It is possible to knock two slates at the same time.



7.4

Slate 'scissors'. One piece at a time is cut from the edge inwards to the predetermined point.



7.5

Dry stone retaining walls in modern road construction.

7.1.4 Crushed stone or stone block?

Crushed stone is the only stone commonly used today in foundations and structural work, either as aggregate in concrete or as levelling or loose fill under foundations. In his essay 'Stone Technology and Resource Development', Asher Shadmon (1983) points out the inconsistency in first crushing stone blocks and then using them in concrete, which in itself is an attempt to copy stone. The extraction and working of stone requires relatively little energy, and at the same time it is a very durable material.

In recent years rough-hewn granite blocks have experienced a minor renaissance; for example in steps, kerbs and other outdoor edgings. Here, compared to concrete, durability as well as aesthetics plays a role. In retaining walls (often seen alongside roads and embankments) large dry stone blocks can quickly be positioned by machine and this has become competitive, especially where the blocks can be quarried locally (Figure 7.5). This provides a solution that combines a good use of resources and very small energy and environmental impact.

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8 Soil materials

'Soil materials' is a collective name for fine-particled materials that have originated from mineral or organic, decomposed products from animals and plants. Seen in the larger lifecycle, these eventually return to a solid form such as rock. During this process, soil materials with a large organic content can form the basis for the creation of coal or oil, which are mostly plant deposits crushed geologically over a very long timespan. Within these states of continuous degradation and regeneration, a wide spectrum of raw materials has been used for building construction throughout history (Table 8.1).

As well as being the starting point for all of the Earth's food production, soil materials have many different uses in the building process: sand and gravel as aggregate in concrete, clay mixed with earth which can be rammed for solid earth construction and clay for production of bricks, ceramic tiles and expanded clay pellets (Table 8.2).

In contrast to minerals, soil materials are defined by their physical properties rather than their chemical properties. Physical properties include grain size and form (see Table 8.3).

Different types of aggregates derive their names from the predominant size of material they contain – a minimum of 60%. The remaining

Table 8.1 *Soil materials in the building industry*

Material	*Areas of use*
Clays and silts	Earth constructions; plasters; claddings and flooring; production of bricks, ceramics and expanded clay pellets
Sand	Sound insulation in floors; aggregate in concretes, plasters and mortars
Gravel	Aggregate in concretes

Table 8.2 *Basic materials*

Material	*Main constituents*	*Areas of use*
Bricks, roof tiles	clay, sand, slag, fly ash, lime, fossil meal	Structures; wall cladding; flooring; roof covering; moisture buffering
Ceramic tiles	clay, kaolin, pigments, glazing	Flooring; wall cladding
Expanded clay pellets	Loose materials containing clay	Thermal insulation; sound insulation; aggregate in lightweight concrete products

Table 8.3 *Soils defined by grain size*

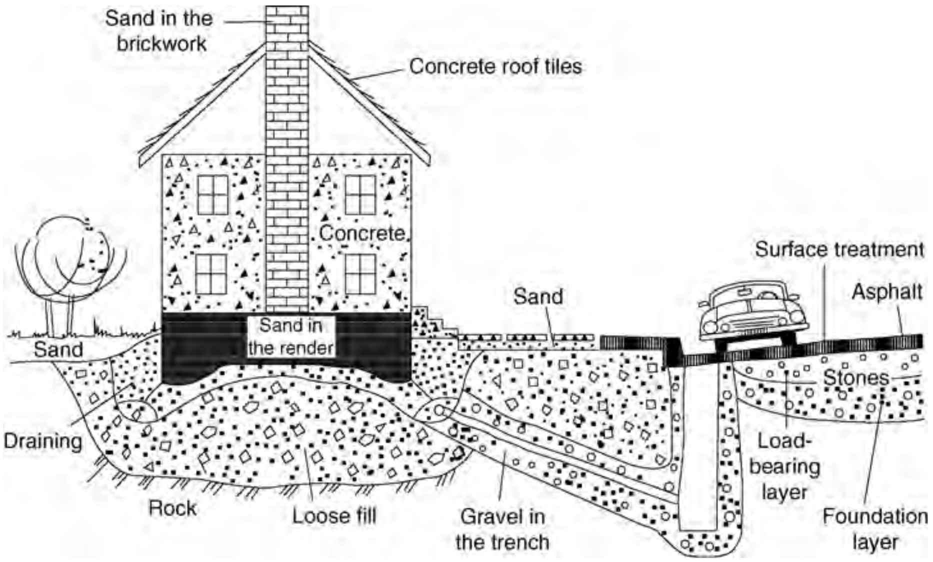
Material	*Grain size (mm)*
Clay	Less than 0.002
Silt	0.002–0.06
Sand	0.06–2.00
Gravel	2.00–64.00

percentage, if more than 20%, is used to define more closely the quality of that material; for example, 'gravelly sand'. They can have a quite pure mineral content, or they can be mixed with organic substances such as peat and mud, mostly mould and plant material, known as humus. Soil material that is well-suited to cultivation is not suitable for building, as it contains organisms and humus acids which have negative effects on both earth construction and concrete.

8.1 SOIL MATERIALS IN BUILDING

Many parts of Europe do not have easy access to gravel and sand as a building material – not necessarily because the resources are not there, but because extraction would have too much impact on the local environment. Certain types of clay, e.g. clay used for ceramic tiles, can also be limited in some regions. Otherwise, deposits of argillaceous materials are very large and well-distributed. Their use, however, is limited – in fact, this material is an almost unused resource. It will continue to be available as a valuable resource in the future.

Extraction of soil materials for use in the building industry requires low energy consumption. Drilling and explosives are unnecessary. It often takes place in quarries, and if these are large they can damage



8.1
The use of sand, gravel and stones for building.

Table 8.4 *Material pollution from the production of materials from soils*

Raw materials/basic materials	*Polluting substances*
Sand and gravel	Dust (possibly containing quartz)
Earth for construction purposes	Dust
Fired clay products with low lime content	Carbon dioxide, sulphur dioxide, fluorine compounds, dust, possibly chromium
Fired clay products with 15–20% lime content	Carbon dioxide, possibly chromium, dust

groundwater and local biotopes. The most suitable clay for the production of bricks and ceramic tiles is usually in the 4–5 metres nearest the surface.

A large amount of water is used in brick manufacture and also in the production of expanded clay pellets and ceramic tiles when grinding the clay. The ceramics industry in Italy has developed an efficient re-circulating system with a simple filter for the waste sludge. In this way they have reduced the quantity of water used and kept the sludge effluent to a minimum.

The energy consumption for firing clay products is very high (see Table 8.5). Fossil oil is the usual source of energy, but wood, peat or a combination of electricity and coal can also be used. When oil alone is used large amounts of greenhouse gas carbon dioxide, acidic sulphur dioxide and nitrogen oxides are released. The brick industry has become increasingly more centralized in Europe. This has resulted in heavier energy consumption for transport and distribution.

Heated clay emits pollutants such as sulphur and fluorine compounds. These can be neutralized by adding 15–20% lime to the clay. The firing process at high temperatures can transform a largely silicate clay with a relative low intrinsic health hazard into forms of crystalline silica, which as dust is hazardous if inhaled (Curwell *et al.*, 2002).

The building of an earth house causes minimal pollution. Vibrations from the ramming machines (see ‘Pisé’, page 210) can cause physical

Table 8.5 *Embodied energy in soil materials*

Products	*Temperature required in production (°C)*	*Embodied energy (MJ/kg)*
Sand and gravel	–	0.5
Earth, compressed	–	0.5
Vitrified bricks	1050–1300	3.5
Well-fired bricks	800–1050	3.0
Medium-fired bricks	500–800	2.5
Low-fired bricks	350–500	2.0
Cellular bricks	1000 (approx)	3.5
Ceramic tiles	1100 (approx)	8.0
Expanded clay pellets	1150 (approx)	3.0
Zytan	1200 (approx)	4.0

harm to the operator. As far as locally built houses are concerned, there is probably no other technique that can compete with the earth house in terms of the lack of environmental impact. The most common building techniques use earth that is dug out of the ground on the site itself. As the volume of material is large, transporting earth long distances is not normally economically viable.

The use of fired or unfired clay products in building causes no problems. In many cases they also improve indoor climate by regulating moisture levels.

Clay building waste is inert, and depositing both fired and unfired products has no detrimental effects on the environment. Exceptions are brick or ceramic tiles that are coloured with pigments containing heavy metals, fire-proof bricks that contain soluble chrome, and bricks from sooty chimneys which have absorbed large amounts of aromatic hydrocarbons during their lifespan. These products have to be separated and disposed of specially.

Bricks have proven to be considerably more effective than concrete in resisting the effects of modern air pollution. They are usually considered to be maintenance-free and have very high durability. However, all brick has a degree of porosity that makes bricks susceptible to frost damage. Such damage is likely to increase in northern Europe with global warming, but to decrease farther south.

Roof tiles and brick can usually be re-used, the latter depending upon the strength of mortar used – Portland cement mortar is much more difficult to remove from the bricks. Other fired clay products, such as ceramic tiles and expanded clay pellets, are seldom recycled and are more usually downcycled to become filler materials. Roof tiles and bricks can be broken up and used as aggregate in concrete.

When an earth house is demolished, the earth is physically and chemically intact in its original form. It can therefore be easily returned to the earth. To demolish a house of rammed earth, either the roof can be taken off and the rain allowed to wash it away, or it can be hosed down with water.

8.2 SAND AND GRAVEL AS AGGREGATE IN CEMENT PRODUCTS

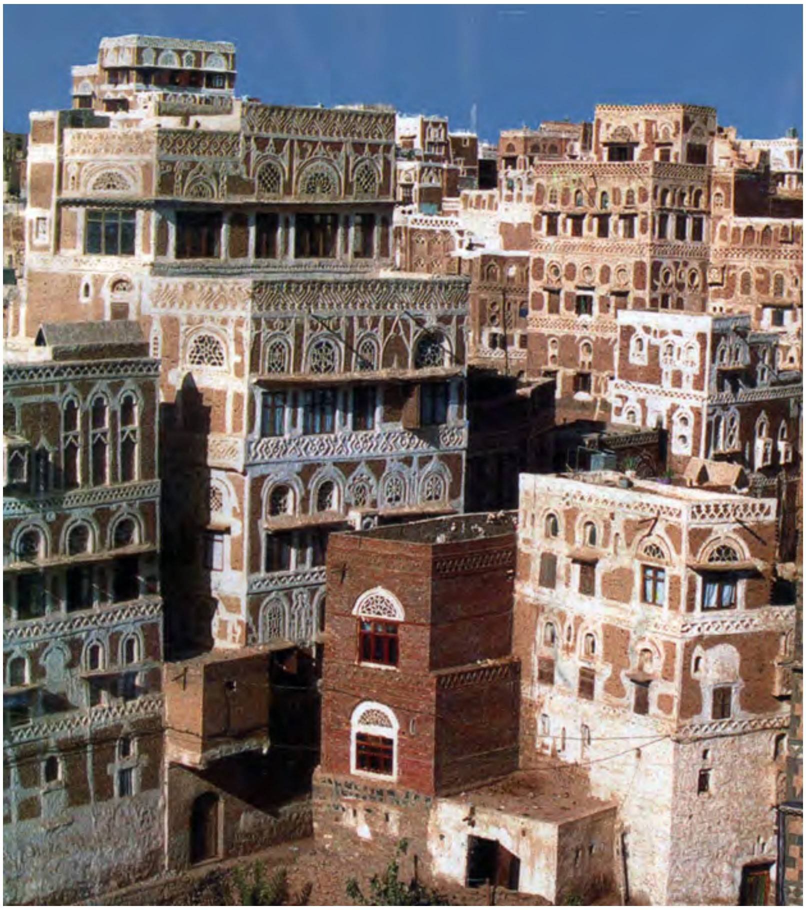
Sand and gravel are the main constituents in most mortars and concretes. These aggregates must be able to tolerate chlorides and alkaline conditions as well as humidity and frost. They must also have the required mechanical strength. Irregular-shaped gravel and sand is best, whilst river sand with rounded grains is far inferior because it offers less bonding surface to the cement. It should be as free of sulphur and earth impurities as possible; mica content can greatly weaken gravels since it provides a slip surface. Inland sand is considered to be best. It is possible to use coastal sand but contact with salt water means that it will contain chloride that corrodes steel. This can be washed out with fresh water.

Sand should not be too fine, except for final coats of wall rendering, which need to be very smooth. The basic principle influencing the choice of sand and aggregates for mixing in concrete is that the grains should be of varied sizes. In this way, the smaller ones fill up the spaces between the larger ones, and far less cement is thus needed to cover all of the grains in the mixture. Therefore, a correct mix of grain sizes in a concrete mix has a big effect on how strong it will be, given a fixed amount of cement.

8.3 EARTH AS A BUILDING MATERIAL

In 1982 a large exhibition and conference took place at the Pompidou Centre in Paris entitled ‘A forgotten building practice for the future’. The theme was earth as a building material. Earth is, even today, the second most widespread building material in the world after bamboo. More than 30% of the world’s population live in earth houses, mainly in less industrialized and developing countries. However, since the beginning of the 1980s, earth as a building material has experienced a renaissance both in Europe and in Northern America. The most important environmental arguments for earth building are that:

- it is based on a resource that is abundant in nearly all countries. In many cases the material can be excavated on site.
- it requires far less energy than is needed for concrete and fired brick buildings.



8.2

Traditional earth buildings in Yemen.
Source: Tyabji.

- if it is carried out correctly, it has a long life expectancy.
- it is based on reasonable and simple building methods which make self-help feasible.
- it provides good indoor climate due to its temperature and moisture regulating properties.
- unfired earth materials can be returned to nature more easily than any other material.

There are two main ways of building earth houses: ramming (pisé) where the earth is rammed between shuttering to make walls, and earth block (adobe) where the earth is first pressed into blocks and dried before use. In addition, there are many variations within these two main techniques.

Argillaceous marine earth is considered the best raw material for earth building. It is also possible to mix clay with other types of earth. Earth can be used in its natural state, and stabilizers such as cement or bitumen can be added to increase cohesion. It can also be mixed with straw, wood fibre or expanded clay pellets for reinforcement or to increase the insulation value. Given a good mixture, homogeneous earth construction has strong structural properties. There are examples of German earth houses up to six storeys high. As with other stone and cast materials tensile strength is poor, and arches or vaults are necessary over openings. Earth structures reach their ultimate strength after a few years. During the first months the walls are soft enough to be chased for electric fittings and to have holes bored for pipes, niches, etc.

The only serious enemy of earth construction is damp – careful design and construction is necessary to avoid damp problems, such as rising damp from the ground. Even a small detailing error can lead to problems. Concrete is tougher than earth in such situations.

Earth-building is very labour-intensive compared to most modern building methods. Within modern economic systems, where all the labour must be paid for, and is expensive, building with earth has become uneconomical.

Earth technology is, however, undergoing intensive development in both Europe and the United States (Figure 8.3). The processes can be simplified and partly mechanized. This includes commercial production of hollow and dense earth blocks at prices much lower than those of brick and concrete. There is now a larger choice of earth and clay based products, including ready-to-use mortars, floor and wall tiles, building sheets and acoustic panels. Pressed products often have natural fibres added for reinforcing and robustness during transport.

HISTORY

Earth buildings have probably been used for over 10 000 years. The oldest sun-dried blocks found are from an area located in the upper Tigris basin, and date back to 7500 BC. In a grave at Giza in Egypt there are traces of 5000-year-old cast earth blocks. English archaeologists have found similar 3000-year-old construction techniques in Pakistan. In the Old Testament, references are made to earth blocks made with straw added: one of the Pharaohs gave orders that the children of Israel should not be given straw to make their blocks (Exodus, Ch. 5, v. 7). Because of its abundance, earth has been used for most of the 'architecture without architects'. There are many historical examples of pure earth towns, from Jericho to Timbuctoo, including temples, churches

8.3
Earth building at Ile d'Abeau in France. Photo: Alice Reite.

and palaces. Both the tower of Babylon and the Great Wall of China were partly constructed of earth.

In both Peru and Chile, the Incas knew of these building techniques long before the Europeans came. The Mexican pueblo is the result of a well-developed earth block technique. Earth building can be found in most cultural periods in world history. An old Irish chronicle tells a story of the patron saint, Patrick, building a rectangular church of earth on the Emerald Isle. In the small French village of Montbrisson is a chapel, La Salle de Diana, built with earth blocks in the year 1270; it is now the town library.

Earth building in central Europe flourished from the end of the eighteenth century and continued until the late nineteenth century. The method became particularly popular in Denmark, England and Germany. After the First and Second World Wars earth houses became popular once again. Towns and villages in Russia destroyed by the fighting were rebuilt in rammed earth, and in Germany around 100 000 earth houses survive from these periods.

8.3.1 Finding and extracting raw materials

Earth for building should contain as little humus as possible. It must be firm with a good compressive strength and a low response to moisture. The most appropriate earth is found in moraine areas, as the grain size is suitable and the proportion of clay in the earth is within the limits of 10–50%. Clay can also be found in earth originally formed underwater – under the 'marine border', which varies according to geographical location but is usually around 220 m above sea level.

It is said that in Romania, where earth houses have been the most common form of building to the present day, even the children can classify the earths. Correct perception has become a tradition. The approximate clay content can be estimated through rolling out earth samples and judging their thickness, as shown in Table 8.6.

Table 8.6 *Estimating the clay content of earth*
Source: Låg, 1979.

Thickness when rolled	*Content of clay (%)*
Cannot be rolled out	Less than 2
3–6 mm rolls	2–5
Approx 3 mm rolls	5–15
Approx 2 mm rolls	15–25
Approx 1–1.5 mm rolls	25–40
Approx 1 mm rolls	40–60
Rolls thinner than 1 mm	More than 60

Source: Låg, 1979.

8.3.2 Deciding technical properties

Many methods have been developed to test the properties of earth. The following is based on a method recommended by the German industrial standard (DIN 18952). There are quicker and simpler methods, but their results are less reliable. There are also chemically based methods.

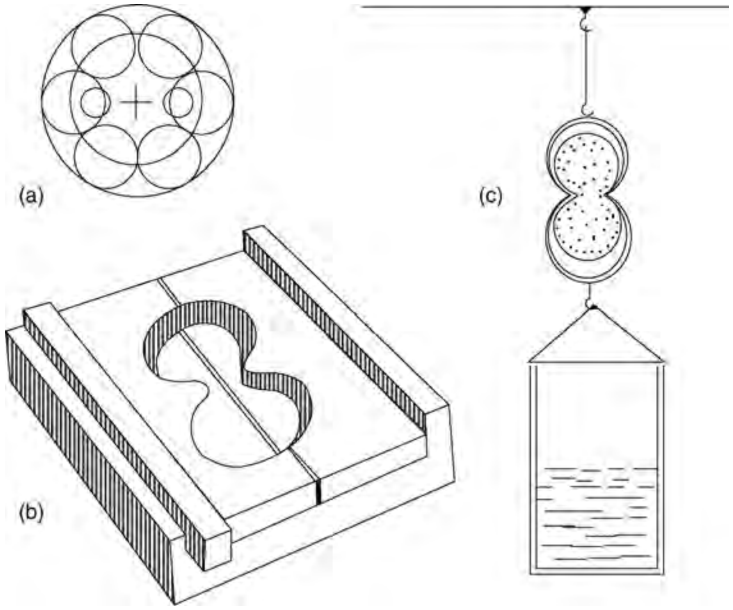
ASSESSING THE BINDING TENSILE STRENGTH

As with concrete, it is an advantage to have an even proportion of different sized particles in the earth, and no larger stones. A well-graded clay binds better since smaller particles fill the gaps between the larger ones. There are usually two tests to assess the binding tensile strength. In both tests, moist earth samples are kept under a damp cloth for 6–12 hours before testing:

- *The ball test* tests stiffness. A sample of 200 gram of earth is rolled into a ball, which is then dropped from a height of 2 m on to a glass surface. If the diameter of the flattened ball is less than 50 mm after impact, then the earth is good enough.
- *The figure-of-eight* tests the cohesion between the particles and can also be used for testing concrete. The earth is knocked into the figure eight form in three layers with a wooden hammer (see Figure 8.4). The mould has specific proportions and can be made of either hardwood or steel. The thickness of the mould is 2.23 cm. The hammered piece of earth is taken out and hung between two circular steel rings. It is then loaded with weight in the form of sand in a small vessel at a rate of not more than 750 g per minute. The pouring is stopped when the sample breaks. The weight under which the sample breaks, divided by the section of the sample, which is 5 cm^2, indicates the tensile strength 'binding power' of the earth. At least three samples should be made to achieve a precise picture of the strength properties. An earth with a binding power of less than 0.050 kp/cm^2 is unusable.

ASSESSING COMPRESSIVE STRENGTH

There is a clear connection between the binding power and the compressive strength. DIN has a standard curve from which the compressive strength can be read as a result of the figure-of-eight tests (see Figure 8.5).



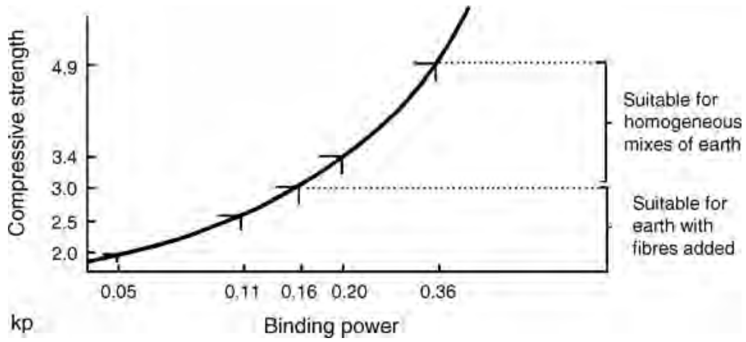
8.4

Equipment for determining the strength of earth using the 'figure-of-eight' technique. (a) Construction of the figure-of-eight mould (DIN 18952). The diameters from the largest to the smallest circle are: 78 mm, 52 mm, 26 mm, 10 mm. The distance between the two smallest circles is 22.5 mm. (b) The mould in which the earth is rammed to a thickness of 22.3 mm. (c) The compressed piece of earth is placed between two steel grips with D = 140 mm, and sand is poured into a container hanging on the lower part of the sample.

8.3.3 Moisture and shrinkage

Earth that holds its shape has a moisture content of 10–23% in its natural state. The more clay, the more moisture it can contain. Thoroughly dried walls have a moisture content of 3–5%. This means that earth with a naturally high moisture content will shrink considerably during drying. To assess the moisture content of the earth, a sample is weighed, dried, then re-weighed. The moisture content is the equivalent of the difference between the two weights.

Generally speaking, earth with a high moisture/clay content is best used for an air-dried earth block. Most of the shrinkage will have taken place before the blocks are laid. Through adding plenty of natural fibres, an earth rich in clay can be used for ramming as in the pisé technique.



8.5

Determining compressive strength based on the results in the 'figure-of-eight' test, see Figure 8.4. The practical potential of the earth can be read on the right.

8.3.4 The preparation of earth

Once the earth has been selected using the above methods, the topsoil, which contains organic matter and humus, is removed to a depth of 20–30 cm. The earth uncovered is then sieved through a steel net with mesh size of about 2.4 cm for ramming earth, or 1 cm for the production of blocks. If the earth has a variable moisture content, it must be well mixed and stored under a tarpaulin for three to four weeks.

Where necessary, stabilizers or extra sand or clay can be added either during sieving or later with an earth grinder. Mixtures stabilized with cement and lime must be used immediately; others can be stored, but they must be covered with a tarpaulin to preserve the moisture.

8.3.5 Earth structures

Any earth to be used for construction is transported straight to the building site without any industrial treatment. Here it is put into casts to make blocks, or rammed between shuttering to make walls. Mortars are also easily prepared on site. More industrialized products such as tiles and panels can be made in small local industries.

8.4 BRICK AND OTHER FIRED CLAY PRODUCTS

> **If brick had been discovered today, it would undoubtedly have been the sensation of the century.**
>
> **(Hoffmann)**

Clay is formed by the grinding and disintegration of rock. In a dry state, clay can be described as $Al_2O_3 \times 2SiO_2 \times 2H_2O$, which means a high content of silicon dioxide. By adding water, clay becomes workable. The process is reversible.

Clay can be formed and fired up to 1000 °C. All water is then evaporated so the formula becomes $Al_2O_3 \times 2SiO_2$, and this change is irreversible. Water cannot be reintroduced into the clay. It has become a ceramic material, with areas of use that have been the same for thousands of years, in construction, on floors and roofs, as water pipes and tanks. When the temperature in specially built kilns is increased even more, the clay begins to expand, turning into expanded clay pellets, which in recent years have become an important insulation material and a light weight aggregate in concrete. If expanded clay is poured into moulds and heated to an even higher temperature, it melts and becomes a highly insulating building block called Zytan.

HISTORY

'The Chinese invented the compass, gunpowder and the brick' is an old saying amongst brick makers. It could well be true, as archaeologists have unearthed a Chinese burnt clay tableaux that can be dated back 6000 years. The first traces of building bricks are from between 1000 and 2000 years later. In Asia there are remains of 4000-year-old brick buildings. In Bombay a brick kiln from about the same period has been found. Between 900 BC and 600 AD the Babylonians and Assyrians developed a comprehensive brick building technique. In Egypt, a pioneering country in many areas, sun-dried blocks were used, except for the occasional use of stone, possibly because of lack of fuel for firing. Brick remains have been found deep in the silt of the Nile, which could mean that there was once brick production even in this area. In Greece, burnt clay probably came into use during the Golden Age of Athens, around 400 BC. The main product was roofing tiles. The Etruscan walls near Arezzo were built a few years into the Christian epoch and are probably among the first brick structures in Italy. The Roman brick industry developed very quickly and produced a whole series of brick elements for both decorative and structural use.

The brick industry in Europe really developed during the eleventh century, and since then brick has been the dominant building material in towns. Since 1920 concrete has become a major rival, but brick now seems to be enjoying a renaissance, partly because of its higher durability and for aesthetic reasons.

8.4.1 Brick manufacture

The argillaceous materials used to manufacture bricks must be easily workable and not contain large hard components or lumps of lime. The latter can cause splitting of the brick when it is exposed to damp. The clay can contain lime, but it has to be evenly distributed. It is an advantage if the clay is well mixed with sand. Clay with too little sand is not easy to shape, but has the advantage of not shrinking so much when drying or being fired. Sand can be added to clays that are too ‘fatty’. The quality of a clay mix can be found through doing some simple tests; it must easily form into a ball, and keep any fine line impressions made by a hand. During drying it must become hard, and without too many fine cracks.

One thousand square metres of clay can produce about 650 000 bricks per metre of depth. The clay does not usually lie too deep in the ground, so it is relatively easy to extract. This is usually done by first scraping away the soil, then extracting the clay and, after re-planning the area, replacing the topsoil.

After the clay has been extracted it is covered with water. At one time, the resulting mixture would have been worked by hand with a special hoe or by ramming. This operation is now carried out by a machine which grinds the clay down to a fine consistency. Additives to reduce its fattiness can be put in the clay and the mixture is then well kneaded. If the clay is stored for between one and three months it becomes more workable and produces a better quality final result.

Sand can be used to make the clay leaner, but slag, fly ash and pulverized glass are also suitable. These not only reduce the amount of shrinkage but make the clay easier to form. The porosity of brick can be increased by adding materials which burn away when the stone is fired, leading to higher insulating values and often bette moisture regulation properties. Materials that can be used for this are sawdust, dried peat, chopped straw, pulverized coal or polystyrene pellets. Porosity can also be increased by adding 15–20% of mineral materials such as ground lime, dolomite or marble; however, these produce carbon dioxide when fired, but at the same time bind the released sulphur and fluorine into harmless compounds such as gypsum.

Insulating materials such as fossil meal can also be added in parts of up to 90%. Fossil meal is a form of earth that consists of air-filled fossils from silica algae. The resulting block has good insulating properties and high porosity. Around Limfjorden in Denmark there is a naturally occurring clay containing nearly 85% fossil meal. It is called molere, and a complete brick industry is based around it. The resources, however, are very limited.

Forming

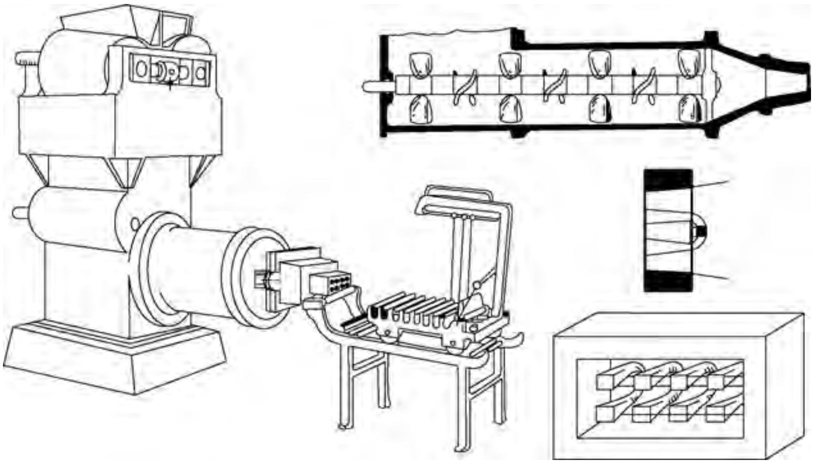
Clay needs a water content of approximately 25% in order to be formed. Forming is carried out mechanically by forcing the clay through a die or just by knocking the clay by hand into a mould. Mechanical hand presses are also used.

The industrial die presses the clay through a mouthpiece into a long 'sausage' with a cross-sectional area allowing for shrinkage (see Figure 8.6). Different sizes of mouthpiece and square or round pegs form holes in the clay sausage. Roof tiles can also be produced in this way. The sausage is cut into blocks on a bench. Mobile dies also have equipment to prepare the clay before pressing, and are used where there are smaller deposits of clay.

Handmade bricks are made by filling wooden or metal moulds in the same way as earth blocks, and striking with a piece of wood. The moulds are sprinkled with sand or dipped in oil or water between strikings. A 'brickstriker' and two assistants can produce 2000 ordinary bricks, 1200 flat roof tiles, or 600 profiled tiles in a day. Even if machine-cut bricks are considerably more economical, the handmade brick with its rustic character is more attractive as a facing brick. As recently as 1973 it was estimated that 99% of all bricks produced in India were handmade (Spence, 1974).

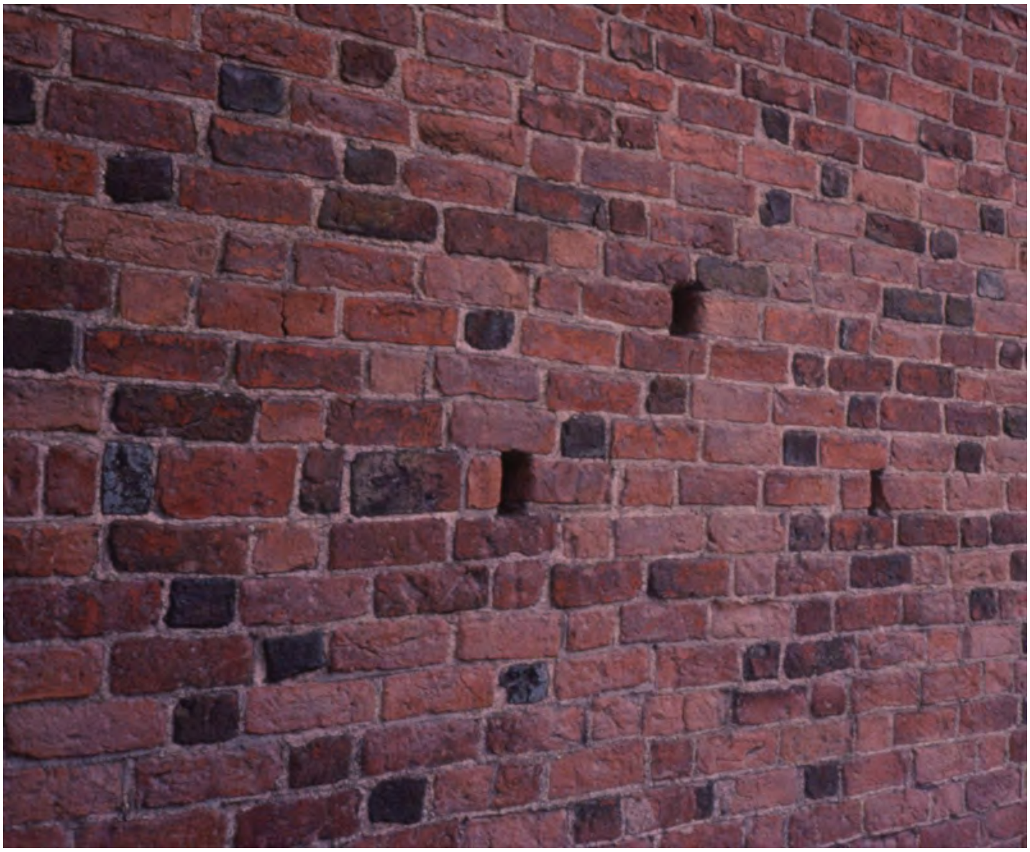
Drying

The unfired brick products are stacked for drying under an open roof for one to two months. If manufacturing is done in winter, bricks may need to be stacked inside heated rooms. This increases the energy consumption a good deal. In modern brick factories special drying houses are kept very hot for two to five days.



8.6

The industrial die with a mouthpiece.



8.7

Colour of bricks vary with composition of clay and firing temperature.

Firing

When clay is heated up to boiling point the water in the pores evaporates, and at 200–300 °C the hydrate water evaporates. After this change, the clay will not revert to soft clay with the addition of

8.8

Small-scale open charcoal kiln in India.

Source: Pratheeps.

water, unlike an air-dried earth block. In the Roman Empire, bricks were not fired in temperatures higher than 350–450 °C; as can be seen in the case of a great many buildings that still stand today, such as the Roman Forum.

If fired at higher temperatures, the particles are pressed closer to each other and the brick becomes harder. Between 920 and 1070 °C the material begins to sinter. If the temperature is increased even further, the blocks will melt. However, higher temperatures are used in the production of fireproof bricks and porcelain, using special clay mixtures. To a well-trained ear, the temperature at which a brick was fired can be assessed by hitting it with a hammer; the higher and purer the sound, the higher the temperature of the firing. This is especially useful when recycling old bricks.

Clay containing iron turns red when fired, whereas clay containing more than 18% lime turns yellow. There are many different colour variations, also determined by the amount of oxygen used during the firing process. Red brick can vary from light red to dark brown.

Chamotte is produced from clay with a low iron and lime content. It can withstand temperatures of up to 1900 °C.

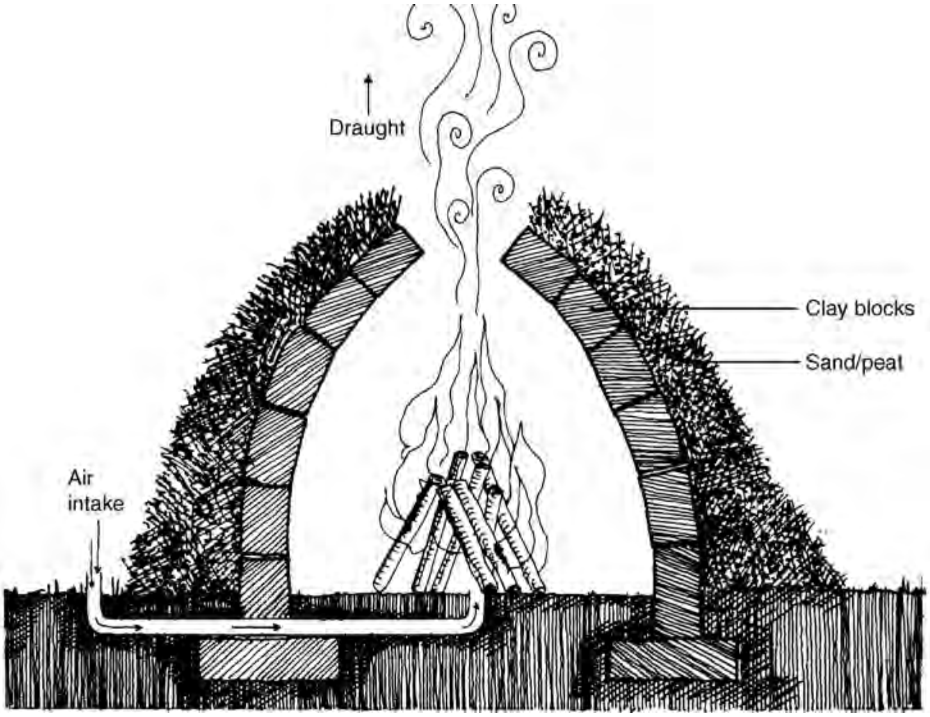
In certain products the brick can be glazed or coloured by the manufacturer using compounds such as oxides of lead, copper, manganese, cadmium, antimony and chromium. To set the glaze onto the brick requires a secondary firing until the glaze melts. The temperature of this firing should be well under the brick's firing temperature so that it does not lose its form.

Kilns

Many different types of kiln have been used over the years; there are three main types: the open charcoal kiln, the Hoffman kiln and the tunnel kiln. It is interesting to note that development of the brick kiln and the baking-oven has run parallel to each other.

The *open charcoal kiln* is the earliest type, used in smaller brickworks as late as the early twentieth century. It consists of two permanent, parallel kiln walls in brick. At the bottom of the walls or between them at the ends there are a series of openings for feeding in the fuel. Clay blocks to be fired are stacked up according to a very exact system. The top layer is a solid layer of ready-fired bricks with some openings for the smoke. They are then covered with earth. The firing takes about two days of intensive burning. The bricks are left in the kiln to cool slowly over a period of several days before the earth and the bricks are removed. A brick factory should therefore have two or three kilns to ensure continuous production. Firing in an open charcoal kiln is not very economical with regard to energy consumption. If production is local, the compensation for this is that transport energy is drastically reduced.

A small, unusual and totally new version of the open charcoal kiln has recently been developed in the Middle East (see Figure 8.9). The 'kiln' is in fact a whole house, which is fired. The clay blocks are stacked up into walls and vaults in their air-dried state. A thick layer of earth is placed over the whole building and a huge bonfire is then lit inside. A door or hole in the roof is required so that the fire can be loaded with wood. After a couple of days, firing is complete. The building then needs



8.9

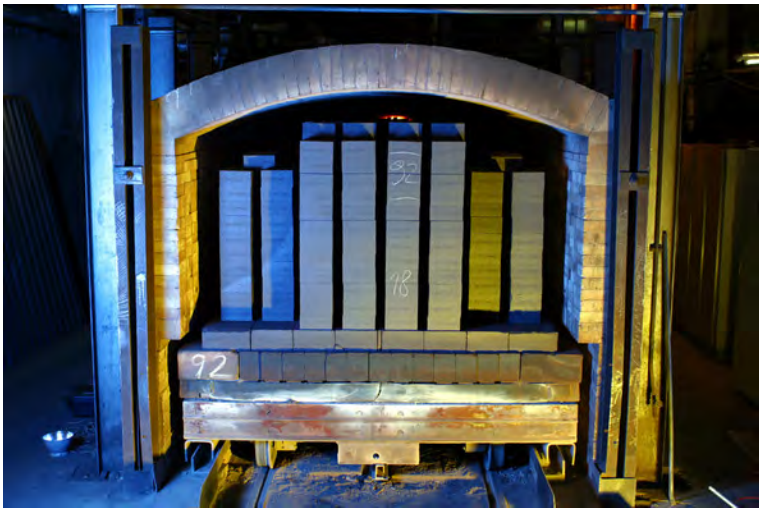
Firing clay blocks that in themselves form the walls of the kiln.
Source: Khalili, 1983.

another couple of days to cool down. The earth is removed, the windows are knocked out and any cracks in the walls are filled.

The *Hoffman kiln*, unlike the charcoal kiln that has to be cooled after each firing, can be kept in continuous use. The firing zone can be simply moved from chamber to chamber. Each chamber is fired for a set period before the heat moves to the next chamber. A complete rotation takes about three weeks. The bricks are fired with sawdust or fine coal-dust sprinkled down through small openings in the roof of the chambers. In modern brickworks where these circular kilns are still used, it is more usual to use oil as a fuel.

The *tunnel kiln* came into use after the Second World War (see Figure 8.10). This kiln can be up to 120 m long and is divided into a preheating zone, a firing zone and a cooling zone. The unburned clay bricks are placed on a truck that moves slowly through the kiln. The energy source can be coal, gas, oil or electricity. Dust exposure is much lower in the tunnel kiln as the operator does not need to enter the kiln. The *roller kiln* is a modification of the tunnel kiln where the bricks are transported on refractory rollers. In the roller kiln, clay with lower humidity levels can be used and the heating time is reduced. Today roller kilns are primarily used for sanitary stoneware products and ceramic tiles, but are also becoming common for brick production.

There is a big difference in the energy consumption of different kilns. The open charcoal kiln uses about twice as much energy as the Hoffman kiln, whilst the Hoffman kiln uses slightly more energy than large tunnel kilns. In roller kilns energy use is reduced by a further 30% (Gielen, 1997). Energy consumption during firing in the Hoffman kiln and the tunnel kiln varies a great deal depending upon the product being



8.10

Tunnel kiln.
Source: RHI.

fired, and falls considerably with lower firing temperatures, to about 60% for medium-fired products.

Sorting

There is an uneven distribution of heat in an open charcoal kiln. The bricks at the outside are usually less well fired than those in the middle. There is some wastage in the Hoffman kiln, but much less than that occurring in the open kiln. Tunnel kilns give the most even heat distribution and wastage is minimal, even if the outermost bricks have a tendency to sinter.

8.4.2 Manufacture of ceramic tiles

In the third dynasty in Egypt, small glazed tiles in light blue, green and black were used to decorate the steps of the Saqqara pyramid. Nowadays ceramic tiles are widely used in both public buildings and dwellings. Their increased use in housing is largely a result of the development of the private bathroom with associated ceramic fixtures.

Quarry tiles and *terracotta* are produced from damp pressed clay in the same way as bricks, using the same raw materials. It is normal to fire the clay until it sinters, at up to 1000 °C.

Vitrified ceramic tiles and *faience* are fired from dry pressed clay, often with ground kaolin; a white clay also used in the porcelain industry. Finely ground waste glass can be added to increase the volume of the mix in proportions up to 75% (Lippiatt, 2007).The product is fired until vitrified, and the resulting tile is much more exact and smooth than products made from damp pressed clay.

All tiles can be glazed. There are three forms of glazing: salt glaze, lead glaze and earth glaze, which can also have pigments added in the form of metal oxides or salts (see Table 8.7). Many of these are environmental toxins, and there are strict rules as to how these materials are disposed of as waste products. Salt glaze is pure sodium chloride (NaCl) which is sprinkled on during firing and reacts with clay to produce a silicate glass. This process needs high temperatures and requires

Table 8.7 *Examples of pigments used for glazing ceramics*

Colour	*Alternative pigments*	*Percentage*
Yellow	Antimony trioxide	10–20
	Chrome chloride	0.5–1
	Ferric oxide	1–2
	Vanadium oxide	2–10
	Uranium oxide (rare)	4–10
Red	Cadmium oxide	1–4
	Chrome oxide	1–2
	Manganese carbonate	2–4
Green	Copper carbonate	1–3
	Chrome oxide	1–3
Blue	Cobalt carbonate	1–3
	Nickel oxide	2–4

very high quality clay. Lead glaze and earth glaze are applied to ready-fired products, which are then fired again.

Tiles that are coloured all the way through are usually vitrified and the added pigments are the same as those used in glazes.

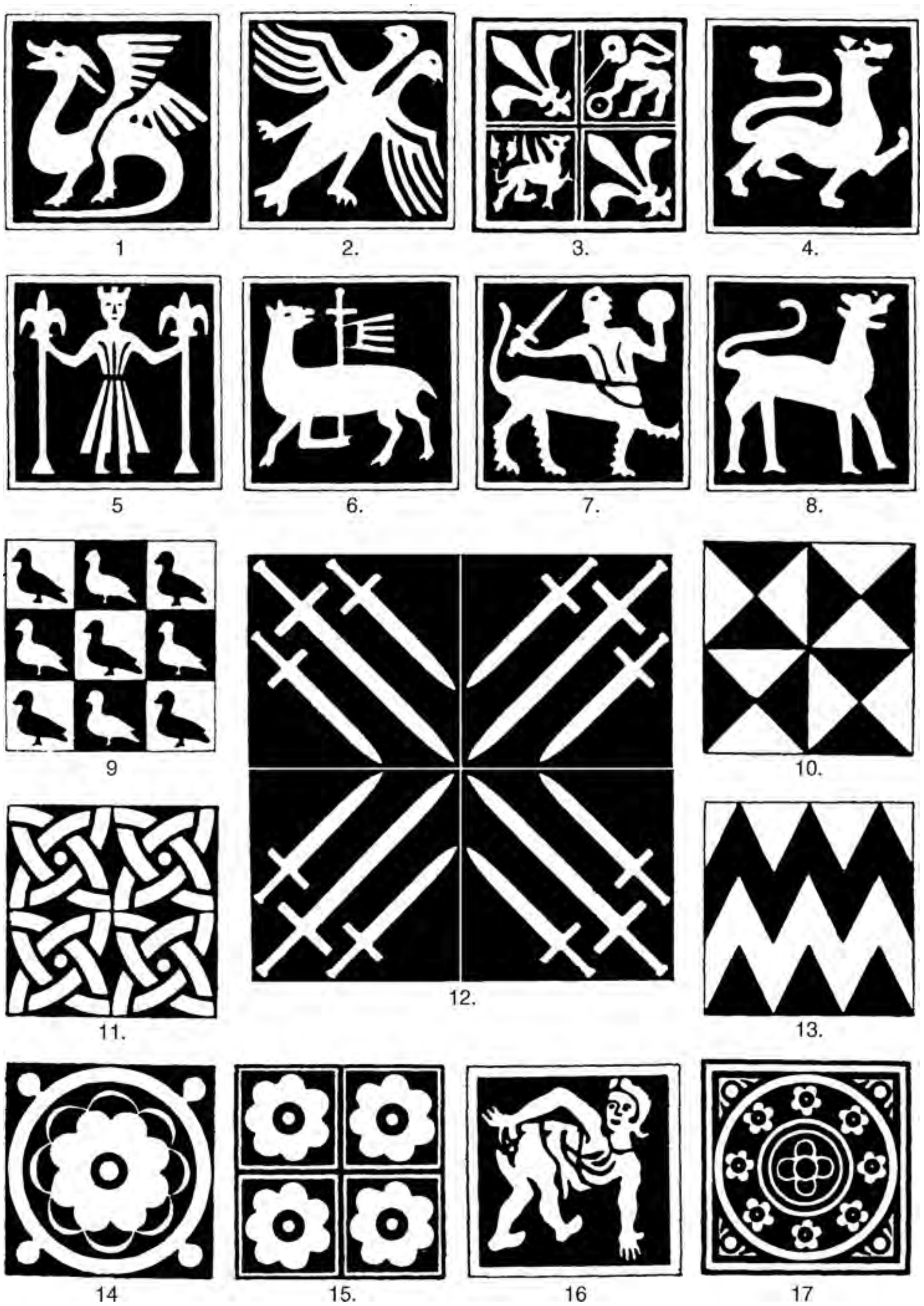
8.4.3 Production of light expanded clay

All clays can be expanded, though some expand more easily than others. And melting must not occur before the clay has expanded – this mainly depends upon the minerals in the clay. The ideal clay is very fine, with a low lime and high iron content.

Clay used for the production of expanded clay pellets needs to air for about a year before being used. It is then ground, mixed with water and made into pellets. Medium-quality clay can have chemicals added, mostly ammonia sulphite in a proportion of 3% volume of the dry clay, and sodium phosphate in a proportion of 0.1%.

Expansion can occur in a vitrifying kiln where sawdust, oil or coal can be mixed with the clay and then fired. Alternatively, the more efficient rotating kiln can be fired with coal dust, oil vapour, natural gas or biogas. The rotating kiln usually consists of a metal cylinder with a diameter of 2–3 m and a length of 12–60 m. There are also smaller, mobile models (see Figure 8.12). The kiln temperature is about 1150 °C and the firing time from clay pellets to expanded clay pellets is approximately seven minutes.

For the manufacture of a light clay block Zytan moulds are filled with light expanded clay, then heated at temperatures of about 1000 °C (Brien *et al.*, 1978). The light clinker expands even more. The spaces within the mould are filled and the material becomes a solid block. Once the moulds have cooled down, the result is a homogeneous and highly insulating thermal block which can be used immediately. The density of



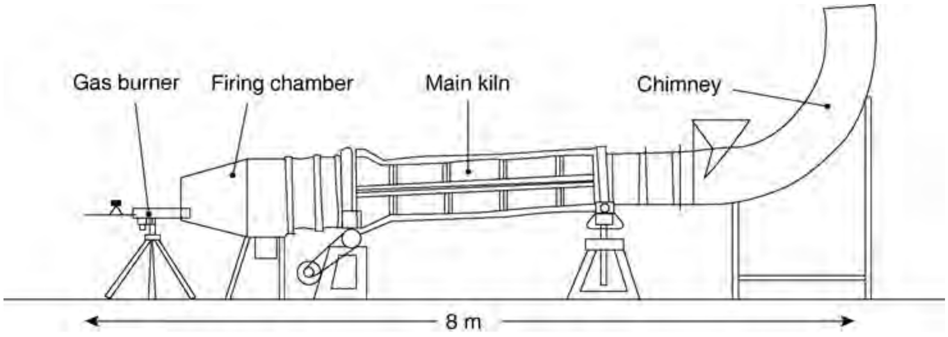
8.11

Examples of English patterns for tiles from around AD 1200.

the blocks can vary from 200 kg/m^3 to 1200 kg/m^3 depending on the firing temperature. All blocks are loadbearing. Holes can be sawn and drilled, just as in other light clay blocks. At present these blocks are not produced commercially.

8.4.4 Fired clay products and reduced energy consumption

Energy consumption in the manufacture of fired clay products is very high and thereby also energy related pollution; above all, emissions of the greenhouse gas carbon dioxide where firing is based on fossil fuels.



8.12

Section through a Pakistani mobile rotating kiln for the production of expanded clay pellets. The kiln is about 5 m long with an inside diameter of 500 mm. The rate of production is about 125 kg per hour.

Source: Asfag,1972.

The brick industry uses large amounts of oil-based energy to dry the unfired brick before firing. The required temperature here is relatively low, which means that solar energy and recovered waste heat from the kilns could be used. Recovered heat could also be used to preheat the kilns.

As noted, the consumption of energy in the kilns depends on the type of kiln, the roller kiln being the most effective. Perforated and hollow products also require relatively less energy, as do products where biomass is added. However, there is probably most to gain by using products fired at lower temperatures. Many bricklayers will remember the routine of using low and medium-fired bricks as the internal leaf in cavity walls and well-fired bricks on the outside. Only vitrified and well-fired bricks are commonly available on the market today unfortunately. Since the use of energy increases by about 0.2 MJ/kg for every 100 °C increase in the firing temperature, the brick industry could reduce its total energy consumption substantially by returning to differentiated firing. This could go a step further by using *unfired* bricks for internal or rendered non-loadbearing walls. There is no technical barrier to this, even in large buildings (see Figure 14.12). The unfired brick also has exceptionally good moisture regulating qualities.

Energy consumption is also related to transport. Fired clay products are heavy and industries producing them are relatively centralized. It is worth considering whether it is ecologically sensible to use brick in an area with no local brick factory. This is especially relevant for areas that cannot be reached by water, since transportation by boat uses less energy.

Simple technology and the relatively widespread availability of clay gives brick and clay tile production many potential advantages for local manufacture. For light expanded clay products it should also be possible to have competitive manufacture at the local or regional level, as well as mobile manufacturing plants.

Recycling must also be considered, since the energy consumption in manufacture is so high. Fired clay products are very durable. For bricks fired at high temperatures, a lifespan of 1000 years seems feasible (Gielen, 1997; Minke, 2006). The energy needed to remove and clean these materials after use only represents 0.5% of the energy required for manufacture. However, the re-use of bricks is only possible if a weak or medium strength mortar has been used. Products such as roof tiles that have no mortared joints have a very high reusability potential. Bricks can also be ground to pozzolana powder, if they were originally fired at temperatures no higher than 600 °C.

Light expanded clay that is free from mortar, such as in insulation underneath a shallow foundation, can be easily re-used in the same way if it has been protected from roots, sand and earth.

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9 Fossil oils

The most important types of fossil oils are extracted directly from subterranean reservoirs, as crude oil and natural gas. Fossil oils can also be extracted from coal or from oliferous slate or clay.

The refining process is the starting point for many products used in the building industry (Table 9.1). Heavy distillates including tar and asphalt are used directly, mostly for making roofs and joints watertight. Other, more refined, products provide raw materials for a whole spectrum of commodities: glues, waxes and solvents for paints. Fossil oils are also the raw material for most plastics. The plastics industry has developed explosively over the past half century. By 1971 an average apartment contained about 1 ton of plastic. A modern Scandinavian apartment contains 2 to 3 tons of plastics (Plastic Industries of Denmark), in everything from the sheathing on electric cables to floor finishes and window frames (Table 9.2). The building industry uses 25% of all plastics produced.

Distillates from fossil oils are all hydrocarbons. These are chemical compounds containing only carbon and hydrogen.

The explanation of how fossil oils have been formed has changed over the centuries. They were once considered to come from the corpses of those who died during the great flood described in the Bible; theories later claimed that it came from rain from outer space. Today, it is common knowledge that crude oil, natural gas and coal are all primarily formed from animal and plant remains that have accumulated in shallow stretches of sea in prehistoric times, and were later exposed to extreme geological pressure and temperature. A main origin of the North Sea oil is shrimp faeces.

Six thousand years ago the Babylonians jointed their clay block houses with bitumen from asphalt lakes. Wider use of fossil oils did not really start until the nineteenth century, when the industry began with the exploitation of reserves on the American continent. The main use of oil products was as a fuel, and later for waterproofing. It was not until the twentieth century that oils were first used for the commercial production of plastics. Today's consumption is nearly 20 kg of plastic a year for every person on the planet (Stevens, 2002), and an increase by 80% is estimated between 2000 and 2030 (Phylipsen *et al.*, 2002).

Resources of fossil oils are very limited. Existing reserves are estimated to last another 30 to 50 years at present rates of extraction.

Table 9.1 *Basic materials from fossil oils*

Material	*Areas of use*
Bitumen	Roofing felts; wind barriers; damp-proofing; mastics
Plastics	Roofing; flooring; interior cladding; window and door frames and furniture; flashing and gutters; thermal insulation; damp-proofing; vapour barriers and vapour retarders; mastics and sealing strips; wallpaper; paints and varnishes; adhesives
Organic solvents	Additives in paints, varnishes, adhesives and mastics; production of plastics
Other chemicals	Production of plastics; additives in concrete, plastics and plant materials, paints, adhesives, varnishes, biocides

Gas reserves are slightly greater than reserves of crude oil, while coal reserves could last more than 100 years.

After being pumped to the surface, oil and gas are transported to refineries for distillation into different fractions. Some of these are then further processed to produce paints, plastics and other materials. Extraction, refining and production of the final material all cause industrial pollution. Every time an oil tanker unloads, many tons of the lightest hydrocarbons escape into the atmosphere. Fishing grounds and coastal areas can face ecological ruin for decades in the event of an oil blow-out or when oil tankers are wrecked. The catastrophic potential of oil can thus be used as a political weapon – as in the Gulf War when the oil wells of Kuwait were set on fire. The oil industry is similar in character to the nuclear industry in its geopolitical and strategic influence.

The processing of oil to plastics and other materials requires a great deal of energy (Table 9.3) the energy intensity of the plastics industries is similar to that of the metal industries. Large amounts of the greenhouse gas carbon dioxide and acidic sulphur dioxide are released. Many of the additional pollutants from the production process are highly toxic, including hydrocarbons and heavy metals

Table 9.2 *The use of plastic in a typical Scandinavian dwelling*

Area of application	*kg*	*Percentage*
Flooring	800	30
Adhesives, mastics	700	26
Pipework	425	16
Paints and fillers	275	10
Wallpaper, membranes	200	8
Thermal insulation	100	4
Electrical installation	100	4
Sealing strips, skirtings, etc.	50	2
Total	2650	100

Table 9.3 *Embodied energy[1] in selected products based on fossil oils*

Product	*Manufacture (MJ/kg)*	*Combustion value (MJ/kg)*	*Embodied energy (MJ/kg)*
Bitumen-products			
- Bitumen	10	40	50
Plastics			
- Polyethylene	67	43	110
- Polypropylene	72	43	115
- Polystyren EPS	77	48	125
- Polystyren XPS	82	48	130
- Polyurethane	105	30	135
- Polyvinyl chloride	65	20	85
Organic solvents			
- Ethylene glycol	24	44	68
- Methanol	47	30	77
- Xylene	26	47	74
Other chemicals			
- Acrylic acid	32	34	66
- Formaldehyde	23	13	36
- Vinyl chloride	26	30	56

[1] **Note**: The embodied energy is defined as the sum of the energy used to manufacture a product and the combustion value of the product. It is assumed that raw material inputs which are not left in the material are used as energy source or as raw material for other products.

required for processing. This does not affect the natural environment alone. Cancer and chemically induced nerve disorders are more frequent amongst workers in these industries than in the general population. Children born with deformities are more common in areas near plastics factories than elsewhere.

When used in building, oil-based products can release volatile organic compounds either as direct emissions or through chemical reactions with other materials, such as concrete. Organic solvents (for example, in paints) will eventually evaporate completely and are greenhouse gases. These and other emissions from plastics can also irritate the mucous membranes and produce traditional symptoms of a bad indoor climate such as irritation in the eyes, nose and throat, unusual tiredness, headache, giddiness, sickness and increased frequency of respiratory illnesses. Other more serious emissions can cause allergies, cancers or foetal malformation. There has also been a marked increase in deaths due to smoke inhalation from building fires during the last few decades, and one reason for this is the increased use of plastics in buildings (Curwell *et al.*, 2002). Smoke from plastics has also been shown to caused lung damage and hypersensibility amongst firemen (Bakke, 2000).

As waste, the sheer volume of plastics can pose a problem since many plastics break down very slowly in the natural environment. A rapid increase in concentrations of plastics in the oceans has been recorded (Browne *et al.*, 2007). These will quite often include toxic compounds and should best be taken care of at special disposal facilities. When released in nature the potential effect through the food chain can be dramatic.

Asphalt can be recycled quite effectively and mixed into new asphalt. Recycling is also possible for some plastics. All plastics, however, contain additives and impurities that lead to a lower quality plastic after recycling (down-cycling). Even if the energy consumption in recycling is less than in its original manufacture from virgin raw materials, the high energy costs of transport still have to be taken into account, as the plastics industry is highly centralized.

Energy recovery has become a very common option for waste products like solvents, oil-based chemicals and plastics. These have a high energy content, but (with a few exceptions) must be burned in furnaces with special facilities for cleaning the emissions. Even so, there is a chance that very toxic pollutants such as dioxins and heavy metals will be released. Regardless of the combustion technology, carbon dioxide is released in similar quantities to combustion of fossil fuels – since these products have much the same chemical composition.

9.1 THE BASIC MATERIALS

9.1.1 Bitumen and tar

Coal tar can be extracted from mineral coal by condensation. This substance was once used widely in the building industry, but is now almost completely replaced by bitumen. Bitumen is obtained by distilling crude oil at 200–300 °C. It is a strong waterproofing substance used to impregnate materials such as building paper, sheets and jointing mastics, or applied directly to a surface as moisture membrane. These products either contain added organic solvents or are in a suspension of water and finely ground clay. By adding powdered stone, sand or gravel, different varieties of asphalt are produced that can be used for roads, damp proofing of foundations and roof coverings.

The chemical composition of coaltar and bitumen differ greatly. Tar is composed of almost 50% polycyclic aromatic hydrocarbons (PAH), which are very damaging in the environment; bitumen has almost none of these compounds. Both these materials can include precursors of dioxins and are a potentially dangerous source of organic compound seepage. Materials that contain tar or bitumen need to be very carefully disposed of (Strunge *et al.*, 1990).

9.1.2 Solvents and other chemicals

Light distillates can be used directly as solvents or as a chemical base for other products. Amongst these are the monomers, which constitute essential components of plastics (polymers). Solvents are substances that facilitate mixing and penetration of substances such as

Table 9.4 *Hazards of organic solvents used in the building industry*

Substance	*General hazards*
Alcohols[1]	Irritate mucous membranes; larger doses can damage the foetus
Ethanol	
Propanol	
Methanol	
Isopropanol	
Butanol	
Aliphates	Irritate mucous membranes and skin; can act as promoter for carcinogenic substances
Paraffin	
Naphtene	
Hexane	
Aromates	Irritate mucous membranes and skin; some can damage heart, liver, kidneys, nervous system; some are carcinogens and mutagens
Xylene	
Toluene	
Benzene	
Styrene	
Chlorinated hydrocarbons	Highly toxic to most organisms; irritate mucous membranes; liver- and kidney-damage; some are carcinogens and mutagens
Dichloroethane	
Trichloroethane	
Trichloroethylene	
Esters	Irritate mucous membranes and skin; slightly damaging to the nervous system
Butyl acetate	
Ethyl acetate	
Methyl acetate	
Ether alcohols	Irritate mucous membranes
Ethylene glycols	
Ketones	Irritate mucous membranes; slightly damaging to the nervous system
Methyl isobutyl keton	
Acetone	
Terpenes[2]	Irritate mucous membranes; can damage lungs; toxic to aquatic organisms; some are allergens
Limonen	
Turpentine	

Effects of selected substances is detailed in Table 2.5. Emissions of organic solvents will also have a global warming potential GWP of approximately 3 by reacting to carbon dioxide in the atmosphere.

[1] Can be produced from plants.

[2] Produced from plants.

paints and usually evaporate from a finished product, such as in paint that has dried.

The following substances are directly or indirectly used in the building industry.

Ammonia was originally obtained by distillation of nitrogenous vegetable animal waste product, including cow dung. Today ammonia is produced from natural gas. Ammonia is an important ingredient in ammonia phosphates and sulphates which are much used as fire retardants in plant-based insulation materials.

Aliphatic and **aromatic hydrocarbons**. Amongst the aliphatic hydrocarbons are paraffins, naphthenes and n-hexane, whilst the aromatics include substances such as xylene, toluene, benzene, ethyl benzene and styrene. These can be used directly as solvents. Styrene, benzene, toluene and xylene are also necessary chemicals for the plastics industry and the latter two are used in the production of organic pigments. Benzene is the initial source of creosote, which is mixed with coal tar to make the impregnating poison carbolineum.

Chlorinated hydrocarbons are formed when hydrocarbons react with hydrochloric acid. They include important solvents such as trichloroethane, trichloromethane, trichloroethene, dichloroethane and dichloromethane. These substances are used mainly in varnishes, paints and paint removers. Dichloroethane is also an important solvent for synthetic rubber and is often used in mastics with a bituminous base. Polychlorobiphenyls (PCBs) have been used widely in the past but are now very seldom used because of their extreme toxicity. These substances have to a large extent been substituted by the chloroparaffins as softeners and binding agents in putty and mastics and as fire retardants in synthetic rubbers. Chloroparaffins are also used as secondary softener in PVC floor coverings.

Fluorocarbons are chemical compounds that contain carbon-fluorine bonds. Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) also contain chlorine atoms and are widely used as a foaming agent to make insulation products of polystyrene and polyurethane. These substances are stable in the lower part of the Earth's atmosphere, but when they reach the stratosphere solar radiation is strong enough to break down their molecular structure, releasing chlorine atoms which react with natural ozone and break down the ozone layer (see Table 9.5). The ozone depleting effects of the HCFCs are only about 10% of the CFCs, which were the major cause of ozone layer depletion and have been phased out fairly successfully since the Montreal Protocol of 1989. Hydrofluorocarbons (HFCs) are fluorocarbons without this problem, and are now replacing the CFCs and HCFCs in most products. The HFCs are less ozone depleting, but like all fluorocarbons still very potent greenhouse gases (see Table 9.5). Perfluorosulphonates are fluorocarbons much used as flame retarders in carpets.

Brominated hydrocarbons. Hydrocarbons react with bromine to form the brominated hydrocarbons. These are much used as flame retardants in plastics; hexabromocyclododecane (HBCD) in insulation foams

Table 9.5 *Fluorocarbons used as foaming agents in the plastic industry, their Ozone Depletion Potential (ODP) and Global Warming Potential (GWP)*

Substance	*CAS No*	*ODP value*	*GWP value*
CFC-11	75-69-4	1	3800
HCFC-22	75-45-6	0.055	1700
HCFC-141b	1717-00-6	0.11	630
HCFC-142b	75-68-3	0.07	2000
HFC-134a	811-97-2	0	1300
HFC-152a	75-37-6	0	140
HFC- 245	460-73-1	0	950
HFC-365	406-58-6	0	890
Pentane	109-66-0	0	11
Carbon dioxide	124-38-9	0	1

ODP is defined as the relative amount of degradation to the ozone layer compared to CFC 11 = 1. See definition of GWP in Table 2.3. Alternative foaming agents of pentane and carbon dioxide are used for comparison.

of polystyrene, tetrabromobisphenol A (TBBPA) in epoxy resin, polyurethane and polycarbonate, and polybrominated diphenyl ethers (PBDE) in polyethylene and polypropylene. In Canada, concentrations of brominated flame retardants indoors have been found to be up to 50 times higher than outdoors, indicating that they are volatile (Schmidt, 2006).

Organophosphates are esters of phosphoric acid. They are used primarily as fire retardants in foamed insulation products made with polyurethane and polyisocyanurate, often together with brominated compounds. They are also used in some products of polyvinyl chloride. The main types are Tris(2-chlorethyl)phosphate (TCEP) and Tris(chloroisopropyl)phosphate (TCPP).

Alcohols and aldehydes. The alcohols that are mostly used as solvents, especially in varnishes, are ethanol, propanol, isopropanol, butanol, isobutanol and methanol. Phenol is an important ingredient in different building glues. Through further oxidation of alcohol, formaldehyde (an important glue substance when mixed with phenol and urea) is formed.

Ether alcohols and ketones. Important ether alcohols are glycol ethers such as methyl and ethyl glycol. They are used as solvents and plasticizers; for example, in varnishes. Methyl ethyl ketone and methyl isobutyl ketone are the ketones used as solvents in chloroprene glue.

Amines are produced from hydrocarbons in reaction with ammonia. Amines are most common as additives in plastics, such as silicone and polyester, mainly as a hardener or anti-oxidizer. Amines are the starting point for the production of isocyanate, which is the main constituent of polyurethane. Amines are also used in the production of certain organic paint pigments.

Alkenes (or olefines) is the group name for hydrocarbons with double combinations. Amongst the most important are ethylene and propylene, which are produced from naphtha and function as monomers in the production of polyethylene and polypropylene. Vinyl chloride is produced by chlorinating ethylene and is the main constituent of PVC plastics.

Esters are formed when hydrocarbons react with acetic acid. Butyl acetate, ethyl acetate and methyl acetate are commonly used as solvents in glue, whilst polyvinyl acetate (PVAC), is an important binding agent in certain water-based glues and paints. The acrylates are esters of acrylic acid, oxidized from propylene, and is used as a binding agent in paints and the production of plastics such as polymethyl metacrylate ('plexiglass').

Phthallic acid esters are produced when phthallic acid reacts with alcohols. They are used mainly as plasticizers in a range of plastics and can constitute as much as 50% of the material. Important types are diethylhexylphthalate (DEHP), diisodecyl phthalate (DIDP) and diisononylphthalate (DINP).

9.2 PLASTICS IN BUILDING

Distillates from crude oil and natural gas, mainly naphtha, have become almost the only raw materials used in the plastics industry these days (Table 9.6). Prior to this, distillates from coal and even natural materials such as maize, cellulose, animal and vegetable proteins were used. Some of these are now being reintroduced.

Plastics are substances of natural or synthetic molecular organic material that can be composed to have a very wide variety of properties, including being easy to liquefy and mould. The basic 'building blocks' are called monomers, completed plastics are termed polymers; the reaction is known as polymerization. During production, substances such as chlorine, hydrochloric acid, fluorine, nitrogen, oxygen and sulphur are used as well as oil-based chemicals. Almost all plastics have a rich variety of additives including plasticizers, pigments, stabilizers against solar radiation, softeners, preservatives and perfumes (Table 9.8).

Plastics are divided into two categories: *thermoplastics* and *thermosetting* plastics (Table 9.7). Thermoplastics leave the factory complete, but can be worked to a certain extent with pressure and warmth, and can be cut. Common thermoplastics in the building industry are polyvinyl chloride, polystyrene, polypropylene, polyethylene and thermoplastic polyesters. Polyethylene and polypropylene are often labelled as polyolefins. Important thermoplastic polyesters are polyethylene terephthalate and polycarbonate. Thermosetting plastics differ from thermoplastics in that they are not finished products; the product is completed by secondary companies or at the building site where hardeners are added. In this group we find the two-component plastics, as epoxy and polyurethane, and synthetic adhesives like phenol-formaldehyde and urea-formaldehyde. Synthetic rubbers are a subgroup of thermosetting plastics with

Table 9.6 *Important building related oil based chemicals with environmental risk*

Oil based chemical[*]	*Area of use*
Acrolein	Polyester, polyurethane, acrylates, etc.
Acrylic acid	Acrylic plastics and paints
Acrylonitril	Styren butadiene rubber(SBR), acrylic fibres
Amines	Silicone, polyurethane, epoxy, organic pigments in paints
Benzene	Polystyrene
Bisphenol A	Polycarbonate, epoxy, polyvinyl chloride
Butadiene	Acrylonitrile butadiene styrene (ABS), Styrene butadiene rubber (SBR), polystyrene
Cadmium	Stabilizer in polyvinyl chloride
Carbendazim	Silicone
Chlorofluorocarbons (CFC)	Polystyrene foam, polyurethane foam
Chloromethane	Silicone, butyl rubber (IIR), polystyrene foam
Chloroparaffins (CP)	Softeners and flame retarders in polyvinyl chloride, polyurethane, sealants and paint
Chloroprene	Chloroprene rubber and adhesives
Decabromodiphenyl ether	Flame retarder in polyamides and polyolefins
Dichloroethane	Polyvinyl chloride
Dichloromethane	Polyurethane foam
Dimethylethanolamine	Polyuretane, epoxy
Epichlorohydrin	Epoxy
Ethyl benzene	Polystyrene
Ethylene	Polyethylene
Formaldehyde	Phenol formaldehyde foam, glue in chipboard, plywood, etc.
Hexabromocyclododecane	Polystyrene foam
Hydrochlorofluorocarbons (HCFCs)	Polystyrene foam, polyurethane foam
Hydrofluorocarbons (HFCs)	Polystyrene foam, polyurethane foam
Isocyanates (TDI, MDI, etc.)	Polyurethane, glue, varnish
Methyl metacrylate	Polymethyl metacrylate
Nonylphenol	Pigment paste, alkyd varnish, epoxy paint and varnish
Octabromodiphenyl ether	Flame retardant in acrylonitrile butadiene styrene (ABS) polystyrene, polyamides
Organophosphates (TCEP, TCPP, etc.)	Biocides, flame retardant in polyuretane and polyisocyanurate foams, polyvinyl chloride, adhesives
Phthalates (DEHP, DIBP, BBP, DINP, etc)	Softener in polyvinyl chloride, synthetic rubbers, polystyrene foam, synthetic carpets, paint, varnish, glue
Phenol	Phenol formaldehyde foam, glue in laminated timber, OSB-boards
Phosgene	Polyurethane, polycarbonate
Polybrominated diphenyl ethers (PBDE)	Flame retarders in polyethylene, polypropylene, acrylonitrile butadiene styrene (ABS) polystyrene, polyamides

Table 9.6 *(Continued)*

Oil based chemical[*]	*Area of use*
Siloxanes (Octamethylcyclotetrasiloxane, etc.)	Silicone
Styrene	Polystyrene, polyester, Styrene butadiene rubber (SBR), Acrylonitrile butadiene styrene (ABS)
Tetrabromobisphenol A (TBBPA)	Flame retardant in epoxy, polyurethane, acrylonitril butadiene styrene (ABS)
Tetrahydrofuran	Seam sealer in flooring of polyvinyl chloride
Vinyl chloride	Polyvinyl chloride

[*] See Table 2.5 for details on toxicity.

almost permanent elasticity. Plastics can be foamed, extruded, moulded, rolled out into thin foils, etc.

Polyvinyl chloride (PVC) was one of the early plastics. The polymerization process was discovered by accident by the French chemist Henri Regnault in 1838. PVC was first produced commercially 100 years later. In 1865 celluloid (a mixture of cellulose nitrate and camphor) was patented. Bakelite was the first really successful plastic. It comprised mainly synthetic phenol formaldehyde resins and was patented in 1909. Other milestones in plastics included the first production of polystyrene in Germany in 1930, polyethylene and acrylates in 1933, polyester in 1942 and silicones in 1944.

9.2.1 Pollution related to the most important building plastics

Extraction and refining crude oil and natural gas as raw materials for the plastic industry have a large impact on the environment. Depending on their type, plastics also emit a long list of damaging substances both during production and use, and when they are dumped or recycled. Important here are large emissions of greenhouse gases both as a result of chemical reactions and high energy consumption in the production process (Tables 9.9 and 9.10).

Polyethylene (PE) is polymerized from ethylene (ethene). Antioxidant, UV-stabilizer and pigment are added to a total of 0.5%. The antioxidant is usually a phenol compound and the ultraviolet stabilizer consists of amines or carbon black. Other additives are also used in larger or smaller proportions, such as flame retardants, mainly aluminium or magnesium hydroxide; chloroparaffins can be used as well. Exposure to ethylene (ethene) may occur in the workplace. The majority of polyethylene products do not emit problematic substances in the user phase. As waste they are difficult to decompose, but can be burned for energy recovery without giving off problematic substances with the exception of carbon dioxide.

Polypropylene (PP) is produced by polymerization of propylene. Ultraviolet stabilizers, antioxidants and colouring are usually added. Phenol compounds are used as antioxidants and amines as ultraviolet

Table 9.7 *Plastics in the building industry*

Type	*Important areas of use*
Thermoplastics:	
Acrylonitrile butadiene styrene (ABS)	Pipes, door handles, electric fittings, electrical switches
Cellulose acetate (CA)[1]	Tape, sheeting
Ethylene vinyl acetate (EVA)	Paints, adhesives
Methyl metacrylate (MMA)	Paints
Polyacryl nitrile (PAN)	Carpets, reinforcement in concrete
Polyamide (PA)	Pipes, fibre for reinforcements and carpets (needle-punched carpet), electric fittings, electric switches, cable insulation, sealing strips, tape
Polycarbonate (PC)	Greenhouse glass, roof lights
Polyethylene (PE):	
- hard (HDPE)	Drainpipes, water pipes, interior furnishings and detailing
- soft (LDPE	Vapour barriers and retarders, geomembranes, cable insulation, flooring, roofing
Polyethylene terephthalate (PET)	Fibre for bonding of natural fibres (when melted)
Polyisobutylene (PIB)	Roofing felt, water-proofing membranes
Polymethyl methacrylates(PMMA)	Rooflights, boards, flooring, bath tubs, paint, mastics
Polyoxymethylene (POM)	Pipes, boards, electric fittings
Polyphenyloxide (PPO)	Thermally insulated technical equipment
Polypropylene (PP)	Sheeting, boards, pipes, carpets (needle-punched carpets), electric fittings, electric switches, cable insulation, geomembranes, fibre for melting of natural fibres (when melted)
Polystyrene (PS, XPS, EPS)	Sheeting, thermal insulation (foamed), electrical insulation, light fittings
Polytetrafluor ethylene (PTFE)	Thermally insulated technical equipment, electrical equipment, gaskets
Polyvinyl acetate (PVAC)	Paints, adhesives
Polyvinyl alcohol (PVA)	Fibre reinforcement in concretes
Polyvinyl chloride (PVC)	Flooring, roofing, window frames, vapour barriers, wallpapers, sealing strips, gutters, pipes, cable insulation
Thermosetting plastics:	
Butadiene acrylonitrile rubber (NBR)	Sealants, cable insulation
Butyl rubber (IIR)	Flooring, sealing strips
Casein plastic (CS)[2]	Door handles
Chloroprene rubber (CR)	Sealing strips
Epoxy (EP)	Filler, adhesives, paint, floor finishes, varnishes, moulding of electrical components
Ethylene propylene rubber (EPDM)	Flooring, roofing, sealing strips
Melamine formaldehyde (MF)	Electrical fittings, laminates, adhesives
Metylene diphenylisocyanate (MDI)	Adhesives

Table 9.7 *(Continued)*

Type	*Important areas of use*
Phenol formaldehyde (PF)	Handles, black and brown electrical fittings, thermal insulation (foamed), laminates, adhesives for plywood and chipboard
Polyisocyanurate (PIR)	Thermal insulation (foamed)
Polysulphide rubber (T)	Mastics, selants, adhesives
Polyurethane (PUR)	Thermal insulation (foamed), adhesives, varnishes, paints, mastics, sealing strips moulding of electrical components
Silicone rubber (SR)[3]	Mastics, vapour repellants, electrical insulation
Styrene butadiene rubber (SBR)	Flooring, sealing strips, water-proofing membranes
Unsaturated polyester (UP)	Roof lights, window frames, gutters, adhesives, clear finishes, floor finishes, rooflight domes, tanks, bath tubs, boards, paint
Urea formaldehyde (UF)	Light-coloured and white electrical fittings, socket outlets, switches, adhesive for plywood and chipboard, toilet seats, thermal insulation (foamed)

[1] Produced from cellulose.
[2] Produced from milk.
[3] Based on silicon dioxide, but polymerization requires the help of hydrocarbons.

Table 9.8 *Additives in plastic products*

Area of use	*Additive /type of plastic*[*]
Antioxidants and ultraviolet stabilizers (0.02–1.8% by weight)	Phenols (e.g. bisphenol A)/various; phosphorous compounds/various; hydroxyphenyl benzotriazoles/various; soya oil/PVC; lead compounds/PVC; organic tin compounds/PVC; organic nickel compounds/PVC; barium–cadmium compounds/PVC; calcium–zinc compounds/PVC
Anti-static agents (up to 4% by weight)	Ammonia compounds of alkanes/various; alkyl sulphonates, sulphates and phosphates/various; polyethylene glycol, esters and ethers/various; fatty acid esters/various; ethanolamides/various; mono- and diglycerides/various; ethoxylated fatty amides/various
Colour pigments (0.5–1% by weight)	Zn, Cu, Cr, Ni, Nd, Pb/various
Fillers (up to 50% by weight)	Zinc oxide, wood flour, stone flour, talcum, kaolin/various
Fire retardants (up to 10% by weight)	Chloroparaffins/PE, PP,PS, PVC,UP; brominated hydrocarbons, EPS, XPS, PUR, PC; organophosphates/ABS, PE, PP, PS, PUR; aluminiumhydroxide/various; magnesiumhydroxide/various; antimon trioxide/PE, PVC, PS
Foaming agents	CFCs/XPS, PUR, UF, PF; HCFCs/XPS, PUR, UF,PF; HFCs/XPS, PUR; Pentane/EPS, PF, PUR; CO_2/EPS, PUR; oxygen/UF; water/PF
Lubricants	Stearates, paraffin oils, paraffin waxes, amide waxes/various
Smoke reducer (approx. 2.5–10% by weight)	Aluminium trihydrate/various; antimony trioxide metals/various; molybdenum oxide/PVC
Softeners (up to 50% by weight)	Phthallic acid esters/various; aliphatic esters from dicarbon acid/various; esters from phosphonic acid/various; esters and phenols from alkylsulphonic acid/various; esters from citric acid/various; trimellitate/various; chlorinated paraffins/various; polyesters/various

[*] Abbreviation, see Table 9.7.

Table 9.9 *Material pollution from basic plastics in production (**P**) and in the house (**H**)*

Plastic[1]	*Potential emissions*[2,3]
Chloroprene rubber (CR)	Butadiene (P), Chloroprene (P)(H)
Epoxy (EP)	Bisphenol-A (P), epichlorohydrin (P), amines (P)(H)
Ethylene propylene rubber (EPDM)	Hexane (P)
Melamineformaldehyde (MF)	Phenol (P), formaldehyde (P)
Polyamide (PA)	Benzene (H), ammonia (H)
Polycarbonate (PC)	Dichloromethane (P), bisphenol-A (P)(H)
Polymethylmethacrylate (PMMA)	Acetonitrile (P), acrylonitrile (P)
Polysulphide rubber (T)	Formaldehyde (P), toluene (P)(H), chloroparaffines (P)(H)
Silicone (Si)	Chlorinated hydrocarbons (P), Xylene (P)(H), amines (P)(H), siloxanes (P)(H)
Styrene rubber (SBR)	Styrene (P)(H), xylene (P)(H), butadiene (P), hexane (P)(H), toluene (P)(H), amines (P)(H)
Unsaturated polyester (UP)	Styrene (P)(H), dichloromethane (P)
Ureaformaldehyde (UF)	Formaldehyde (P)(H)

[1] See main texts for info on polyethylene (PE), polypropylene (PP), polystyrene (PS), polyurethane (PUR) and polyvinyl chloride (PVC).
[2] Emissions from optional additives, e.g. flame retardants, are not included. Additionally there will be large emissions of carbon dioxide from the production of all plastics.
[3] See Table 2.5 for details on toxicity.

stabilizers, to a total of about 0.5%. Other additives are used in variable proportions, in some flame retardants.

Exposure to propylene during its manufacture can be damaging, although there are no dangerous emissions from the finished product.

Table 9.10 *Combustion gases emitted from plastics in fires and waste treatment*

Type of plastic	*Potential combustion gases*[1]
Acrylonitrile-butadiene-styrene (ABS)	Carbon monoxide, hydrogen cyanide, nitrogen oxide
Chloroprene rubber (CR)	Carbon monoxide, hydrogen chloride, dioxines
Melamine formaldehyde (MF)	Carbon monoxide, hydrogen cyanide, ammonia
Polyamide (nylon) (PA)	Carbon monoxide, acrolein, hydrogen cyanide, hydrogen chloride, nitrogen oxide
Polycarbonat (PC)	Carbon monoxide
Polyisocyanurate (PIR)	Carbon monoxide, hydrogen chloride, acrolein
Polymethylmethacrylate (PMMA)	Carbon monoxide (large volumes)
Polystyrene (PS, EPS, XPS)	Carbon monoxide, benzene, styrene, formaldehyde
Polyurethane (PUR)	Carbon monoxide, nitric oxide, nitrogen dioxide, acrolein, benzonitrile, acetonitrile, ammonia, hydrogen cyanide, isocyanates, aromatic hydrocarbons
Polyvinyl chloride (PVC)	Carbon monoxide, methane, hydrogen chloride, phosgene, cadmium, dioxines
Styrene butadiene rubber (SBR)	Carbon monoxide, sulphur dioxide, nitrogene oxides
Unsaturated polyester (UP)	Carbon monoxide, benzene, styrene, formaldehyde

[1] Large emissions of carbon dioxide coming from incineration of all plastics are not included, see Table 2.8. When chlorinated, fluorinated or brominated additives are used there will also be emissions of dioxines. Chlorinated flame retardants will emit hydrochloric acid.

As waste it is difficult to decompose, but it can be burned for energy recovery without emitting dangerous substances with the exception of carbon dioxide.

Polystyrene (PS) is produced by the polymerization of styrene. It can be made into transparent sheeting, but the dominating polystyrene products are foamed expanded polystyrene (EPS) and extruded polystyrene (XPS). Both are used as insulation and the latter, having high resistance to moisture, also in foundations. EPS comprises 98% styrene; XPS only 91%. Additives include an antioxidant, an ultraviolet stabilizer, and often a fire retardant. The antioxidant used is usually phenol propionate in a proportion of 0.1%, amines are used as the ultraviolet stabilizer and the flame retardant is organic bromine compounds, with or without antimony salts, up 1% in EPS and 2% in XPS. An inhibitor can also be included in the product to prevent spontaneous polymerization; this is usually hydrochinon in a proportion of about 3%. EPS is then foamed using pentane and XPS usually with chlorofluorocarbons.

During production, emissions of benzene, ethyl benzene, styrene, pentane and chlorofluorocarbons are quite likely. In production plants the health effects of benzene, ethylene and styrene have been registered.

The finished product can have some unstable residues of monomers of styrene (less than 0.05%) which may be released into the atmosphere, depending upon how the material has been installed in the building. XPS will also release fluorocarbons used as foaming agent.

As a waste product, polystyrene can be environmentally damaging through the leakage of additives. It is also difficult to decompose.

Polyurethane (PUR). The basis for polyurethane is the isocyanates where production involves the highly toxic substance phosgene, known from the Bophal disaster in India in 1984. Isocyanates are amongst the most allergenic substances known. Polyurethane is produced in a reaction between isocyanates (40%) and different polyethers (4%), using organic tin compounds as catalyst. Antioxidants and flame retardants are also used. Phenol propionate is the usual antioxidant, and the flame retardant can be an organic bromine compound. Fluorocarbons, pentane gas or carbon dioxide, in a proportion of 10–15%, are used to foam the plastic.

Substances that can be released during production are chlorinated hydrocarbons, phenol, formaldehyde and ammonia, possibly even organic tin compounds and chlorofluorocarbons. Workers are exposed, not least, to isocyanates – which are considered to be the single most common cause of work-related asthma (Bakke, 2000). Exposure often leads to chronic hypersensitivity. Reaction can be triggered by doses as low as 0.14 μg/m^3 which, in practice, are almost undetectable (Mötzl, 2004).

In the finished product there will often be residues of untransformed isocyanates; for example about 0.5% in polyurethane glues (Zwiener *et al.*, 2006). These will be emitted at normal temperatures. At around 150 °C which can occur near heating apparatus in buildings, the polyurethane compounds themselves can start to break up, leading to much larger emissions of isocyanates. At even higher temperatures, such as in fires, the lethal neurotoxin hydrogen cyanide is formed.

At normal temperatures polyurethane products can also emit small amounts of amines, and significant emissions of brominated compounds have also been registered when these are used as flame retardant (Schmidt, 2006). Emissions of fluorocarbons, if used as foaming agents, will also take place. Approximately 10 to 20% of the amount used will leak out during the first year, and then 0.5 to 1.5% per year thereafter (Harnisch *et al.*, 2004). Environmentally damaging substances can leach out of the waste product, and polyurethane has a long decomposition time.

Polyvinyl chloride (PVC) is produced by a polymerization of vinyl chloride, which in turn is produced from 51% chlorine and 43% ethylene. Bisphenol A is often used as a polymerization inhibitor. Many other additives are also used; for example, about 0.02% antioxidants and ultraviolet stabilizers, a maximum of 10% flame retardants, 2.5–10% smoke reducing agents, up to 4% antistatic agents, 0.5–1% pigment; in some cases as much as 50% plasticizers as well as fillers. Constituents that are critical for the environment are substances such as plasticizers containing phthalates, ultraviolet stabilizers containing cadmium, lead or tin (in the case of windows) and flame retardants with chloroparaffins and antimony trioxide. In PVC gutters, cables and pipes, lead is often used as the ultraviolet stabilizer.

Production plants for PVC are likely to emit chlorine gas, ethylene, dioxins, vinyl chloride, the solvent dichloroethane, mercury and other problematic substances. Certain larger plastics plants have emissions of several tons of phthalates into the air every year. During production, workers can also be exposed to organic acidic anhydrides.

Emissions of phthalates or organic acidic anhydrides (when heated) can occur from the completed product in buildings, together with a series of other volatile substances such as aliphatic and aromatic hydrocarbons, phenols, aldehydes and ketanes, though only in small amounts. Leftover monomers from vinyl chloride may also be released (approximately 10 mg/kg PVC). There is also greater microbiological growth on plastics containing phthalates, which probably functions as a source of carbon and nitrogen.

As a waste product, PVC contains environmentally dangerous substances that can seep out, not least when heavy metals have been used as pigments or cadmium as an ultraviolet stabilizer. PVC is considered to be the largest source of chlorine in waste products. When burnt, it can form concentrated hydrochloric acid and dioxins, the most toxic and persistent of all chemical groups. PVC waste can form hydrogen chloride when exposed to solar radiation. It decomposes slowly.

9.2.2 Durability of plastic products

Many external factors can break down plastics: ultraviolet and visible light, heat, cold, mechanical stress, wind, snow, hail, ice, acids, ozone and other air pollutants, water and other liquids, micro-organisms, animals and plants. The lifespan of plastics is extremely variable, depends

Table 9.11 *The anticipated lifespan of plastics*
(Sources: Grunau, 1980; Holmström, 1984).

Type	*Assumed lifespan (years)*
Butyl rubber IIR	2–less than 35
Chloroprene rubber CR	2–less than 40
Ethylene propylene rubber EPDM	Less than 30
Ethylene vinyl acetate EVA	3
Melamine formaldehyde MF	6–10
Phenol formaldehyde PF	16–18
Polyamide PA	11–less than 30
Polyethylene PE	2–15[1]
Polyisobutylene PIB	11–less than 40
Polymethyl methacrylates PMMA	Less than 40
Polypropylene PP	3–less than 10
Polysulphide rubber T	22–less than 50
Polytetrafluor ethylene PTFE	25–less than 50
Polyurethane PUR	7–10
Polyvinyl chloride PVC	8–less than 30[1]
Silicone rubber SR	14–less than 50
Styrene butadiene rubber SBR	8–10
Urea formaldehyde UF	5–less than 35

Notes: Includes both external and internal use. Positioning in water or earth is not included. The most protected locations achieve the best results.

[1] Does not apply to buried cold water pipes in thicker plastic, which is assumed to last longer.

(Sources: Grunau, 1980; Holmström, 1984).

on its type, its position and the indoor or outdoor temperatures and climatic conditions it is exposed to (Table 9.11).

Plastic products are used in floors, roofs and walls in such a way that it is often difficult and expensive to repair or replace them. They should therefore have a functional lifespan equivalent to other materials in the building; at least 50 years. It is unlikely that most of today's plastics can satisfy such conditions.

Although many plastics have been on the market for over 25 years, new mixtures, additives and modifications are often being introduced. This has often been in order to phase out environmentally problematic constituents. Amongst polymer technicians it is well known that today's plastic products are very different from those on the market only a few years ago. It is therefore difficult to prove the durability of existing products.

The assumed lifespan of a product is usually based on so-called accelerated ageing tests. The material is exposed to heavy, concentrated stresses and strains over a short period. In the early 1980s, Dr K. Berger from the plastics manufacturers Ciba Geigy AG stated that present forms of accelerated ageing test had a 'low level of accuracy at all levels' (Holmström, 1984). Testing methods have not changed much since then, and the picture has not been made easier by the fact that new additives are constantly appearing. It is also recognized that we still do not fully understand the effects of different climate conditions (Shokrieh *et al.*, 2007). PVC is considered to be a plastic with good durability, but it has been known to undergo very rapid breakdown. In Sweden, 10-year-old plastic skirtings crumbled not because of the PVC itself but because of an added compound, acrylonitrile butadiene styrene (ABS), which should have increased the strength and durability. ABS plastics oxidize easily.

Sealing strips of ethylene propylene rubber (EPDM) are often used between elements in prefabricated buildings of timber and concrete. Research has shown that certain types have lost elasticity after as little as only one year. This means that the joint is no longer sealed and the construction no longer functions.

It is very common to tape plastic foils and other plastics-based layers that form the important airtightness or damp proof membranes in buildings. This can be in most areas: walls, roofs, around openings, etc. It has been shown repeatedly, however, that these tape materials can both become brittle themselves, and decay the plastics, quite quickly, with dramatic consequences (Adalbert, 1998).

9.2.3 Recycling

Even where plastics have a relatively short functional lifespan, it can take a very long time for them to decompose in the natural environment. On waste tips, plastic is a problem in terms of volume as well as pollution from the additives that seep into the soil and ground water. Residues of fluorocarbon foaming agents will be emitted continually.

These problems can be greatly reduced by controlled collection and recycling of plastic materials; however, in many countries today only a small fraction of plastics are effectively recovered.

Recycling by re-use of whole components is seldom really practicable due to limited durability and necessary quality assurances being difficult to perform. Material recycling through melting is an option for thermoplastics and even a few of the thermosetting plastics. Amongst these are PVC, polyethylene and polypropylene. Material recycling for purified polyurethane products is also possible, in theory, but is not occurring much at present. Synthetic rubbers can be crumbled for use as a filler.

The maximum potential for future plastics recycling is estimated at 20–30% in the form of down-cycling only. Almost all plastics are impure, due to additives, which makes reclamation of the original materials technically difficult. The quality of the plastic also becomes lower for every cycle performed. After three cycles of recycling polystyrene suffers a 9% reduction in the size of its polymer chains and a 34% reduction in impact strength (Stevens, 2002).

Uses for recycled plastic vary from park benches, sound barriers and flowerpots to huge timber-like prefabricated building units for construction. The latter are now in production in Great Britain, Sweden and the USA, based on melted polystyrene waste with 4% talcum powder and

11% other additives. Polystyrene can also be ground and added to concrete to increase its insulation value.

Energy down-cycling recovers the energy content (calorific value) of the original raw materials. In the case of plastics this is considerable, since they were derived from fossil fuels. However, the problematic polymers and additives often require very advanced combustion technology and flue gas cleaning in order to avoid serious toxic emissions. If one burns plastic wastes, release of carbon dioxide equivalent to burning the same quantity of fossil fuel is also unavoidable. From a climate change perspective, one could thus argue that depositing and storing these materials would be a better option.

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10 Plants

> The forest gives generously the products of its life and protects us all
>
> Pao Li Dung

Until the introduction of steel construction at the beginning of the industrial revolution, timber was the only material with which a complete structural framework could be built. Timber unites qualities such as lightness, strength and elasticity. Compared with its weight, it is 50% stronger than steel. It is more hygienic than other similar materials – the growth of bacteria on kitchen benches of timber is lower than that on benches of plastic or stainless steel. Timber also has low thermal conductivity. On the other hand, the high carbon content of plant materials makes them combustible and more susceptible to biological decay.

However, in relation to most modern European building standards, timber can still be used in up to 95% of the components of a small building. This includes everything from framework and roof covering to thermal insulation and furniture.

There are many non-structural uses for plants from climbing plants that act as a barrier against wind and weather, to linseed oil from the flax plant used in the production of linoleum and various types of paint. Wood tar and colophony can be extracted from wood for use in the

Table 10.1 *Use of plant materials in the building industry*

Material	*Areas of use*
Softwood and hardwood	Structures; wall cladding; flooring; roof coverings; windows and doors; pins and bolts; thermal insulation; fibres; cellulose; chemicals
Climbing plants	Wall cladding; air cleaning
Straw and grass	Roof covering; wall cladding; thermal insulation; minor structures; cellulose; chemicals
Grass turf	Roof covering; minor structures
Moss	Thermal insulation; joint sealant
Peat turf	Thermal insulation

Table 10.2 *Basic plant materials*

Material	*Area of use*
Acetic acid	Disinfectant; bioplastics
Cellulose	Thermal insulation; sound insulation; paper products for wind proofing and vapour retarders; wallpapers
Fatty acids	Paints; varnishes; adhesives; soap treatments; bioplastics
Fibre	Thermal insulation; sound insulation; building boards for cladding, underlay, wind proofing, vapour retarders etc.; reinforcement in concretes, plasters and biocomposites; sealing of joints; carpets
Lignin	Adhesives; additive in concretes; bioplastics
Methanol	Adhesives; paints; varnishes; bioplastics
Potash	Glass production; potassium waterglass
Silicates (siliceous plants)	Pozzolana in cements
Starch	Adhesives; paints; bioplastics
Turpentine	Solvent in paints and adhesives

paint industry and pine oil for the production of soap for treatment of wooden floors. Copal is extracted from tropical woods and is used as a varnish. Natural caoutchouc from the rubber tree can be used in its crude form as a water repellent surface treatment. Oil from soya and linseed, starch from potatoes and maize, methanol and cellulose which can be derived from most plants, form a basis for bioplastics that is likely to become more common in the building industry as fossil oils become scarce. Biocomposites are also experiencing a breakthrough; these consist of plant fibres used as fillers and reinforcement in building sheets. The binder is often cement or plastics but bioplastics are also being tried out.

FLAX – A VERY DIVERSE PLANT

Flax is one of the oldest cultivated plants. The seeds can be pressed to produce oil for use in painting and for producing linoleum. Its fibres can be woven into valuable textiles, pressed into strips for sealing joints around doors and windows, braided into light insulation matting or compressed into building boards.

Flax fibres are twice as strong as polyester fibres; and about 50–75% stronger than cotton (Andersson, 1986). Flax is even stronger when wet. It is naturally resistant to most insects. It is relatively fireproof and can be used as insulation in fire doors. If it does ignite, it smoulders and does not emit toxic fumes.

Plants are renewable resources that can be cultivated and harvested on a sustainable basis. Given sensible methods of cultivation they are a constant source of raw materials.

About 27% of the total land mass is covered by forest. In addition, about 13% is covered by sparse forest (Kucera *et al.*, 1999). In Europe, about 36% of the land is forest – though only 1% of this is old growth forest (Muilerman *et al.*, 2001).

The importance of trees and plants for the global climate is now realized. They break down carbon dioxide, the dominant greenhouse gas, into oxygen and carbon that is stored in the soil and in vegetation. Seen from this perspective it is amazing that rainforests are still being threatened not only by pollution but also by clearing for development. This occurs also in large parts of Australia, Russia and the USA, where timber is felled without replanting.

TIMBER FROM THE TROPICS

The first shipments of tropical timber came to Europe via Venice during the fifteenth and sixteenth centuries. This timber was mainly extracted from the rainforests, which covered about 14% of the Earth's surface at the beginning of the twentieth century. This has now been reduced to about 6%. It has been estimated that about 25% of all global emissions of carbon dioxide are caused by deforestation in the tropics (Gielen, 2000). This accelerates the process of global warming, also creating an increased strain on the forests themselves including extinction of vulnerable animal and plant species.

Tropical timber is used for many purposes, such as window and door frames, interior panelling, floors and furniture, both as solid timber and veneers. Some timbers such as azobè, iroko and bankiria, have qualities useful to ecological building. They have a strong resistance to rot and can therefore be used in very exposed situations without chemical treatment. Despite this, using rain forest timber should be avoided altogether, unless the timber is managed sustainably.

For almost all purposes it is quite feasible to use temperate hardwoods instead of tropical timber. Oak and chestnut are examples. Many other timbers have excellent durability and aesthetic qualities. New solutions with heat treated coniferous timber can attain very much the same appearance as hardwoods, and can fulfil at least half of the same functions (Gielen, 1997).

The production of plant-based building materials is mainly local or regional. Energy consumption for processing and transport are relatively low, as is pollution occurring at the cultivating, harvesting and refining stages (Tables 10.3 and 10.4). This favourable environmental profile will be reflected in the building's overall ecological footprint, as well as by a good indoor climate. Most of these materials also have quite a long life, in particular wherever the conditions of use are fairly dry, and where they can dry out quickly after exposure to rain or humidity. Global warming is expected to cause significantly more rot damage in northern latitudes, whereas Western and Southern Europe will experience a decrease in risk (Noah's Ark, 2006).

When a building decays, organic materials will quickly return back to the natural environment. Alternatively, some of the materials can be recycled for re-use or as a source of energy.

Seen in a global climate perspective, building materials based on plants act as a store of carbon – a 'carbon sink'. One kilogram of dry timber contains about 0.5 kg carbon which is 1.8 kg carbon dioxide bound through photosynthesis. This quantity is thus removed from the global atmosphere for as long as the plant or timber itself lasts – until it rots or burns. Large quantities of timber and other plant products are used in construction, and the amount can be greatly increased. This can thus provide a significant contribution to reducing global warming. A conventional timber frame house contains about

Table 10.3 *Embodied energy[1] in basic plant products*

Product	*Manufacture (MJ/kg)*	*Combustion value (MJ/kg)*	*Embodied energy (MJ/kg)*
Timber, squared and air dried	0.5	16	16.5
Timber, planed and air dried	0.7	16	16.7
Timber, planed and kiln-dried	3.0	16	19.0
Sawdust and wood shavings	3.0	16	19.0
Straw, loose fill and bales	0.5	14	14.5

[1] **Note:** The embodied energy is defined as the sum of the energy used to manufacture a product and the combustion value of the product. It is assumed that raw material inputs which are not left in the material are used as energy source or as raw material for other products.

150 kg/m^2 of timber. Thus a 120 square metres house 'stores' about 32 tons of carbon dioxide. If a building is constructed in logs, or the increasingly popular system of massive timber then this can be increased to about 550 kg/m^2. This means carbon storage of nearly 120 tons of carbon dioxide. This amount almost equals the normal total greenhouse gas emissions of a house during its lifetime, including both its construction and heating. However, the carbon sink must be maintained for a minimum of 100 years in order to be accounted fully in a climate calculation. Long life and maximum re-use of timber and plant-based components are, therefore, important. Where plant products have a lifetime shorter than 100 years, they can only be accounted as a reduced amount of climate reduction.

Whilst most organic materials have this healthy environmental profile, there are a few exceptions. Cultivating plants can involve the use of insecticides, fungicides, hormone additives and synthetic fertilizers that can be responsible for increased erosion, polluted ground water and the damage or destruction of local ecological systems. This type of cultivation can also produce defects such as enlarged and mouldy cell growth in timber. Gene manipulation has been suggested as a solution to reduce the need for fungicides. By adding genes of a more resistant plant, it is possible to reduce the amount of insecticide sprayed on a crop during cultivation. This gives the modified species an 'unfair' advantage over other species in the ecosystem, however, and may lead to the collapse of the whole system. This kind of solution is at present too dangerous to accept as a long-term environmental strategy.

Plant products may also be impregnated against mould, glued with synthetic glues, treated with flame retardants and with chemical paints and varnishes. Many of these additives are problematic, both for nature, for indoor climate and as final hazardous waste.

Generally it can be said that it is desirable to increase the use of organic materials in the building industry. This can considerably reduce the overall climate footprint of production and operation of buildings (Burnett, 2006; Goverse *et al.*, 2001). This is both due to the carbon storage, and the generally lower energy and pollution effects of production. Only a small percentage of the potential organic building materials available are used today. The use of more varied species will stimulate different methods of application and a richness and diversity of species within forestry and agriculture. This is beneficial both to the farmer and to nature.

Table 10.4 *Material pollution from plant materials*

Materials	*Polluting substances*
Trees and grasses (processing)	Wood dust[1]; formaldehyde (coniferous trees)
Cellulose	Lye; chlorine
Fatty acids	Colophony
Terpenes	Turpentine; limonene
Wood tar	Aromatic and aliphatic hydrocarbons

[1] **Notes:** Dust from some trees can be slightly carcinogenous, for example red cedar, oak and several tropical species.

BIOPLASTICS

Trees and plants contain many substances that can replace fossil resources in the manufacture of plastics. The building blocks for plastic include methanol, starch, lignin, oils, proteins and cellulose. Most types of plastics could be produced from plants with the required consistency, chemical and mechanical qualities (Gielen, 1997). At present bioplastics are little used except in fairly short-lived packaging products. For buildings, technical requirements are often difficult to assess and production is still more expensive than plastics from fossil oils. Dwindling fossil resources are likely to change this picture fairly quickly (Stevens, 2002).

Production of the most robust bioplastics requires about as much energy as conventional production (Patel, 2002). Monomers, solvents and additives are likely to have similar toxicological characteristics as those used today, and they are not necessarily easily degradable. Their essential difference from today's plastics is in being produced from renewable resources. They can thus also be regarded as climate neutral, since burning them after use will release the same amount of carbon that was originally bound by the plants from the atmosphere.

BIOCOMPOSITES

By composite materials is meant all materials comprising at least two ingredients, this applies in other words to a majority of building products. However, the term is normally applied to cement or plastics-based materials that are reinforced with fibres. The term 'biocomposites' is used where this reinforcement consists of natural fibres such as wood, hemp, flax or cellulose. If the binder itself is a bioplastic then one has a purely vegetal product. Use of natural fibres has increased in recent years since they often display the same technical performance as synthetic fibres of polyester or fibreglass. Their tensile strength is often slightly lower but this is largely compensated by lower weight (Mohanty *et al.*, 2005). An important use is in cement-based sheets. In many developing countries with scarce timber resources, plastics-based sheeting materials reinforced with natural fibres such as sisal and jute have been marketed for façades and roofing. Other building elements have been developed based on recycled plastic reinforced with wood fibre that can be recycled from demolition products.

Seen from the point of view of resources, substitution with natural fibres is a positive step. The production energy will be considerably lower, and can be halved for some sheet products (Patel, 2002). Generally, composites are not very desirable since they involve irreversible mixing of materials, making material recycling practically impossible. In the case of bioplastics, this picture provides openings for improvement. In some cases the products may even be entirely compostable.

Table 10.5 *Bound carbon dioxide in plant products versus moisture content*

Moisture content (%)	*Bound carbon dioxide (kg CO_2/kg)*
0	1.87
8	1.73
12	1.67
18	1.28
20	1.56
30	1.44
100	0.94

(Source: Beyer *et al.*, 2001; Esser, 1999)

PLANTS IN THE CARBON CYCLE

In nature's processes, carbon is exchanged continually between the biosphere and the atmosphere; the oceans are by far the largest global carbon sink. On a global basis the annual net uptake of carbon in vegetation is about 13 000 million tons of carbon. This is approximately double all emissions from human society. The difference, however, is in the process of being almost annulled by the current deforestation of tropical rainforests.

Plants contain carbohydrates in the form of sugar, starch and cellulose. These are the most important nutritional and accumulative substances in plant organisms. Sugar is formed in the green parts of the plant by carbon dioxide CO_2 from air and water H_2O subjected to sunlight.

$$6CO_2 + 6H_2O + 2822\ \text{kJ} = C_6H_{12}O_6 + 6O_2 \qquad (1)$$

During this reaction, oxygen is released. The plant later transforms sugars to starch and cellulose. Cellulose builds up the cells and the starch is stored. When the plant dies, it degrades back to carbon dioxide, water and ash. Oxygen is a necessary ingredient for this process. If there is very little or no oxygen, the plant becomes peat, and much of the carbon will be transformed to methane (CH_4).

At night, part of the carbon taken up by the plants in daytime is released, but the overall carbon uptake increases as the plant grows, more so during the early years of growth (Table 10.6). After a certain age, which is about 60 years

Table 10.6 *Characteristics of different tree types for carbon storage*

Type	*Annual storage (tCO_2/ha/year)*	*Average fixation (tCO_2/ha)*
Oak/beech	5–6.9	154–535
Spruce	9.7–13	229–510
Poplar, 15 years	13.1	95
Willow, 1 year	15–20	50

Apart from the tree species, their age, the land quality and the climate conditions play an important role. The annual storage can differ 50 per cent in much better or worse conditions.
(Source: Gielen, 2000)

forspruce trees and over 100 for pine, the plants no longer absorb more carbon by day than they release at night.

Harvested plants are largely composed of carbon that has been bound during the plant's growth. The carbon will remain intact until the product is burned or composted. The carbon content of dry plant matter is normally about 50%. In mixed materials the carbon content may be lower, for example around 40% in paper products with mineral fillers added. Each kilogram of bound carbon corresponds to binding 3.6 kilograms of carbon dioxide.

When used plant products are burned the CO_2 is returned to the atmosphere, in the same quantities as were originally bound in the plant. Bioenergy is thus considered to be carbon neutral. On the other hand, if plant material is dumped and buried at waste tips it will rot and produce methane gas (CH_4) due to the lack of oxygen. Methane gas is a much more potent greenhouse gas than CO_2, but the product will still be in balance seen from the emissions point of view. The decomposition of wooden materials takes up to 150 years, and the half life emission time for the CH_4 emissions is about 11 years (Petersen *et al.*, 2002).

10.1 LIVING PLANTS

Plants which can be used in buildings in their living state include grass (*turf*), climbing plants and hedges. All living plants absorb carbon dioxide effectively and produce oxygen. They also bind dust, which make them especially useful in urban areas. Several species have an ability to absorb and break down a range of well-known pollutants including benzene, formaldehyde, tetrachloroethylene and carbon monoxide.

10.1.1 Turf

Turf roofs represent one of the oldest known forms of roof covering in the northernmost parts of Europe, and are still in wide use. In towns and cities in central Europe there is a renaissance of the turf roof and roof gardens. Turf has also been used as insulation in walls. In Iceland, the construction of turf walls with structural properties was widespread right up to the twentieth century.

Ordinary grass turf used for a building should preferably be taken from old mounds or fields to ensure that it is well bound with grass roots. If the grass is relatively young (three to four years old) the root system will be undeveloped, so the turf may break up when removed. Turf should not be taken from a marsh.

Modern turf roofs often start as loose earth that is then sown with grass seed. A recommended mixture consists of 70% sheep's fescue (*Festuca ovina*), 10% timothy grass (*Phleum pratense*) and 20% creeping bent grass (*Agrostis stolonifera*). In dry areas, generous amounts of house leek (*Semper vivum*) and rose root (*Sedum roseum*) – which are very resistant during dry periods – should be added. The *Sedum* can be sown and the *Semper vivum* planted, because it will spread through a rapidly developing root system. *Semper vivum* contains a lot of sap and therefore has a certain

Table 10.7 *Climbing plants*

Species	*Maximum height (m)*	*Growth conditions*
Self climbers:		
Climbing hydrangea (*Hydrangea anomala* and *H. petiolaris*)	4–8	Sun and shade
Ivy (*Hedera helix*)	30	Shade
Virgina creeper 'five-leaved ivy' (*Parthenocissus quiquefolia*)	20	Sun and shade
Virginia creeper 'Lowii' (*Parthenocissus tricuspidata*)	20	Sun and shade
Trellis climber:		
Blackberry, bramble (*Rubus fruticosus*)	2–3	Sun
Chinese wisteria (*Wisteria sinensis*)	6–10	Strong sun
Climbing rose (*Rosa canina*)	3–4	Strong sun
Common hop[1] (*Humulus lupulus*)	10	Sun and shade
Common Virginia creeper (*Parthenocissus vitacea*)	10	Sun and shade
Honeysuckle (*Lonicera pericymenum*)	10	Sun
Winter jasmine (*Jasminum nudiflorum*)	2–5	Strong sun

[1] Plant withers in winter.

degree of fire resistance. When turf roofs were common in towns, laws ensured the use of *Semper vivum* on the roof.

Redcurrants, gooseberries and blackcurrants thrive in roof gardens and on flat roofs with a deep layer of earth. Trees planted on roofs should have a very shallow root system, e.g. birch.

10.1.2 Climbing plants and hedges

Climbing plants and hedges are not often used in building despite their interesting properties. They can reduce the effects of wind, increase warmth and sound insulation, and protect wall materials. There are two main types of climbing plant: those that climb without support, and those that need support (Table 10.7).

Self-climbers need no help to climb and can easily cover a wall. They climb by means of small shoots with small roots or tentacles. The smallest unevenness on the wall gives them a grip. Over a period of time an even, green screen will form, requiring a minimum of care. These types of plants are best suited for high, inaccessible façades.

The most important climber in the northern European climate is ivy. It grows slowly, but can spread out to a height of 30 m, and is evergreen.

Trellis climbers are dependent upon some form of support to be able to climb a wall. There are three types:

- Twining plants need to twist around something to climb. They do not grow well on horizontal planes. Wisteria, honeysuckle and hops are common examples.

- Self-supporting plants have a special growth that attaches to irregularities on a wall or to a trellis of steel or timber. These plants grow strongly and need regular cutting and care. The Virginia creeper is the most common. The wall does not have to be particularly uneven for the plant to be able to fasten onto it; in some cases these plants can be classified as self-climbers.
- Some plants that need support do not fasten either to walls or other objects. They grow upwards quickly and chaotically, and can form thick layers. Blackberry bushes are an example.

If there is no earth along the external walls of a building, most climbing plants can be hung from a balcony. Virginia creeper and blackberry are good hanging plants.

Hedge plants can be planted against a wall and grow independently with a strong trunk, but do not fasten to the wall. They have to be trimmed regularly. Quite a few grow in the northern European climate, such as rose hip.

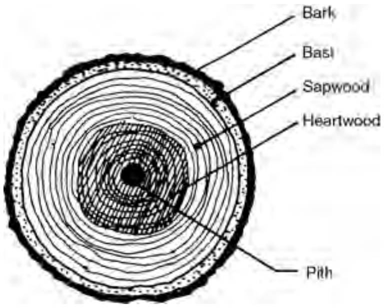
10.2 TIMBER

There is no doubt that the earliest building material in common use was wood, as branches, bushes, etc. (Wright, 2005). Through subsequent ages, people continued to reproduce such light shelters, both permanent and transportable (cf wigwams, yurts, bowers . . .). However, solid log houses appeared in Northern Europe during the Neolithic Period and eventually a complete mastery of joinery and carpentry permitted massive construction with accurately shaped timber.

Trees are mainly composed of long cells stretched vertically, forming wood fibres. Across the trunk are pith divisions, forming rectangular cells. This structure gives timber elasticity and strength. Cells vary in form from timber to timber, but they all contain carbon, oxygen, hydrogen and nitrogen as their main chemical constituents. They also contain small amounts of minerals, which are left in the ashes if the tree is burned. A healthy tree consists mainly of cellulose, lignin and other organic substances such as proteins, sugar, resin and water.

A cross-section of a tree trunk consists of bark, bast, sapwood, heartwood and pith (Figure 10.1). The annual growth rings in a tree are visible because summerwood is darker than springwood. The number of rings gives the age of the tree, and the width of the rings indicates the growth conditions and, therefore, the quality. In coniferous trees, narrow rings usually indicate better quality than wide rings. In deciduous trees wide rings indicate better quality timber.

On the island of Madagascar there are 1000 species of tree. In Northern Europe there are only approximately 35 species, of which about two-thirds can be used for construction (Table 10.8). Despite this, usually only two coniferous trees are used (spruce and pine), and increasingly large areas supporting deciduous trees have been given over to industrial cultivation of spruce and pine forests. There is also a tendency to replace pine



10.1
Cross-section of a tree trunk.

10.2
Logs of pine with large amounts of heartwood.

Table 10.8 *Wood species used as timber*

Species	*Properties*[1]	*Areas of use*
Alder, common (*Alnus glutinosa*)	Not particularly durable in air, very durable under water, soft, light, brittle, twists easily, easy to work	Piles, gutters, plywood, internal cladding
Apple (*Malus pumile*)	Hard, homogeneous, hard wearing, low resistance to moisture	Wooden screws, dowels, thresholds
Ash, common (*Fraxinus excelsior*)	Hard, dense, tough, elastic, low resistance to moisture, easy to bend under steam	Flooring, plywood, internal panelling, stairs, internal structural details
Aspen (*Populus tremula*)	Moisture resistant but strongest when dry, does not twist	Flooring, plywood, suspended ceiling, smaller structures, cladding, piping for water and gutters, piles
Beech, common (*Fagus sylvatica*)	Hard, strong, medium resistance to moisture, twists easily, no smell, easy to work	Flooring, balustrades, smaller structures, plywood, internal panelling, tar, vinegar
Birch (*Betula pubescens* and *Betula pendula*)	Tough, strong, elastic, low resistance to moisture, twists easily, easy to work	Flooring, stairs, internal panelling, plywood, chipboard, bark for damp proofing, smaller structures
Douglas Fir (*Preudotsuga menziesii*)	Durable, easy to work, limited moisture movements, difficult to impregnate	Structures, flooring, cladding
Grey Alder (*Alnus incama*)	Not particularly durable, light and brittle, easy to work	Internal panelling, veneer
Hazel, common (*Corylus avallana*)	Strong and elastic, not particularly durable	Wattle walling in timber framework
Holly (*Helix aquifolium*)	Hard, homogeneous, hard wearing	Plywood
Juniper, common (*Juniperus communis*)	Tough, firm and very durable, difficult to split but easy to work	Cladding plugs
Larch, European (*Larix decidua*)	Tough, strong and durable, good moisture resistance, easy to work, cannot be painted	Structures, flooring, doors, windows, roofing
Lime (*Tilia cordata*)	Tough, medium strong, slightly elastic, easy to work	Smaller structures (used for log buildings in the Carpathians), internal panelling, plywood, fibre for woven wallpaper and rope
Maple (*Acer platanoides*)	Hard, dense, tough, elastic, flexible, hard wearing, low resistance to moisture, easy to work	Flooring, balustrades, stairs, plugs
Oak, English (*Quercus robur*)	Dense, heavy, hard, hard wearing, elastic and durable, tendency to twist, quite difficult to work, moisture resistant	Structures, flooring, windows, doors, thresholds, plugs, cladding, roofing
Plane (*Platanus hybrida*)	Medium resistance to moisture, medium workability	Plywood
Plum (*Prunus domestica*)	Splits easily when dried	Plywood
Rowan or Mountain Ash (*Sorbus aucuparia*)	Heavy, hard, tough, durable, hard wearing, easy to work	Wattle cladding on external walls

Table 10.8 *(Continued)*

Scots Pine (*Pinus sylvestris*)	Soft, elastic, strong, durable, easy to cleave and work, denser and more resin than in spruce, difficult to glue and paint, can be pressure impregnated	Structures, flooring, cladding, windows, doors, tar, roofing, foundations below ground level, plugs
Sitka Spruce (*Picea sitchensis*)	Low resistance to moisture, medium workability	Joinery, cladding
Spruce, European (*Picea abies* and *Abies alba*)	Soft, elastic and medium hard wearing, sensitive to moisture, easy to glue and paint, difficult to pressure impregnate	Structures, cladding, laminated timber, fibreboard
Sycamore (*Acer pseudoplatan*)	Medium resistance to moisture, large moisture movements, easy to work	Flooring
Walnut (*Juglans regia*)	Moisture resistant, medium moisture movement, easy to work	Plywood
Western Red Cedar (*Thuja Plicita*)	Very durable, limited shrinkage, low strength, high resistance to mould, easy to work	Exterior cladding, roofing
White Willow (*Salix alloa*)	Tough, elastic, easy to cleave	Veneer, wattle cladding on external walls
Wild Cherry (*Prunnus avium*)	Stable, hard wearing	Flooring
Wych Elm (*Ulmus glabra*)	Strong, tough, elastic, durable, moisture resistant, not particularly easy to work	Flooring, balustrades, piles, stairs, panelling, internal structural details

[1] Varies according to place of orgin and the conditions of growth.

with spruce, as it produces less waste and is more practical to handle in the sawmill.

Many deciduous timbers have qualities that should encourage their more widespread use in building. In certain areas they are superior to spruce and pine, because of their higher resistance to moisture and greater strength. Ash, for example, is 60 to 70% stronger than spruce. Buildings using only accessible deciduous trees, and using materials according to their strength, could reduce the amount of structural timber needed by 25% (Bunkholt, 1988).

In India, 300 different types of timber were analysed to assess how useful they could be in building. Factors such as weight, strength, durability and shrinkage were investigated. Timber varieties were then graded according to their properties. By doing this a whole new range became available for use in building, including types previously classified as non-resources or firewood.

Timber is often used in its untreated form. Resistance to rot and fungus is most often increased by applying biocides on the surfaces or by pressure treatment where the whole cross-section of the timber is impregnated. There are also less hazardous ways of improving the durability, e.g. heat treatment and chemical modification, see Chapter 19.

Shredded wood in various ways, often from waste and off-cuts, is also common in various building boards such as chipboard. Sawdust and wood shavings are also used as loose filling for thermal insulation. Defibrated wood is shavings treated with humidity so that the binding agents in the wood are softened, then pulped to a mass with fibres of

1.5 mm thickness or more. This increases the specific surface area by 100 000 times and this is the raw material for the production of cellulose as well as for acoustic and thermal insulation in loose form, as matting and boards. Matting and boards often include glues. Harder board products are often produced at high temperatures, and by applying high pressure the natural binders within the wood melt and act as the glue. Fibrous wood mass has also become common more recently as filler and reinforcing in plastic materials.

Latex from rubber trees has been widely used as a water repellant in exterior quality building boards. Tar from conifers is used for surface treatment of timber. And all timber contains useful materials that can be used to produce solvents, bioplastics, etc.

10.2.1 Forestry

Modern forestry is often managed as a monoculture of coniferous trees, mainly spruce. This is especially the case when producing timber for the cellulose industry. Such monoculture forestry leads to acidic soil, and reduces the pH level in the rivers; these forests are, ecologically speaking, near-deserts; few ecological systems can function. They also can cause increased soil erosion due to comprehensive drainage systems that quickly channel rainfall into rivers and streams, and therefore threaten many species of plants and animals.

Forestry can, however, be run on ecological principles. The key lies in the natural regeneration of a varied forest. This requires sowing seeds of a wide variety of local tree species, including deciduous trees that prevent acidity; and careful harvesting so that younger trees and other plants are preserved. There is clear evidence that timber from these mixed forests is of a higher quality than that cultivated in monocultures (Thörnquist, 1990). When felled, the bark is kept in the forest, providing nutrition on the forest floor including nitrogen from coniferous needles that make the addition of artificial nitrogen fertilizer unnecessary.

People used to be far more careful when selecting trees for felling. They chose mature trees: conifers more than 80-years-old, most deciduous trees between 30 and 60-years-old. Beech and oak should be well over 100-years-old to be ready for felling. The definition of a mature pine is that pith and heartwood form at least half of the cross-section of the trunk. In both spruce and pine the heartwood begins to form around the age of 30 to 40 years.

In view of climate change it is becoming important to maximize the capacity of different trees to bind carbon. For example, in spruce, the uptake of carbon slows down considerably earlier than in pine (Liski *et al.*, 2001). One should thus operate with a shorter rotation cycle for spruce than pine – which is in accordance with the conventional view of the maturing times of these species.

The best quality conifers grow in lean soil. Heartwood timber shrinks less than other timber and is more durable, making it well suited to the construction of doors, windows or external details. The demands of quality are lower for the production of cellulose, internal panelling, etc.

In order to make the best of heartwood timber, it used to be prepared while the tree was still standing. This process, called self-impregnation, is known in many cultures, from the British Isles to Japan. The most common method is to lop off the top of the tree and remove a few strips of bark from the bottom to the top. Three or four of the highest branches are left to draw up resin. After two to seven years the whole trunk is filled. There is little growth during these years, but a very high timber quality is produced. The method is especially effective with pine, which contains three times as much resin as spruce.

When timber for felling was first categorized, people would find suitable special features for its use, such as diagonal ties and bracing in post and lintel construction or framework construction. Crooked trees and round growths on the roots of trees proved particularly interesting. The tree could also be worked with and formed while it was still growing to achieve certain particular effects (Figure 10.3). Traditional English framework structures are, in many cases, based on intentionally bent timber. A 'bulge' occurs when a coniferous tree that was bent straightens up, the bulge occurring on the underside of the bend. Timber at this point is close knit and strong and has been used for exposed items such as thresholds. It can be considerably stronger than laminated timber.

10.3

A traditional method of cultivating special qualities in timber.

With today's production techniques, hand picking timber has become uneconomical. Even the quality of timber is given little attention, apart from the desire for straight trunks with few knots. Focus has been on volume not quality. However, there is a growing awareness of issues of both sustainable forestry and timber durability, so there may perhaps be a revival of small, more specialized industries in this field. In Sweden research is now being undertaken to evaluate the possibilities of differentiating qualities of timber in modern forestry, in order to return to a situation where the best quality timber is used in the most exposed situations.

Felling. Both deciduous and coniferous trees intended for construction purposes should be felled in winter when the quantity of sap is at its lowest and the state of swelling and acidity are at their most favourable. Timber felled during spring and summer is more susceptible to mould. Another advantage of winter felling is that the sawn timber dries out more slowly and is therefore less likely to split. Many felling traditions were related to the phases of the moon. Coniferous trees were felled at full moon, as it was assumed that the resins were well drawn out of the roots and into the trunk.

It has been assumed that the large amount of mould damage in newer Swedish timber buildings, especially in windows and external panelling, relates to the fact that the timber was felled during the summer – a usual practice in Sweden during the 1960s (Thörnquist, 1990).

Storage. Although newly felled timber should be treated as soon as possible, it is usually some time before this can be done. The timber should be ideally stored in water, where there is hardly any oxygen. This reduces the risk of mould and insect damage. Timber stored in water during the summer months, however, often becomes porous through the action of anaerobic bacteria that eat the contents of the cells and pore membranes. This can dramatically reduce resistance to rotting, as water is more easily absorbed.

Splitting. The trunk is transported to the site where it is to be milled. Splitting should take place while it is still damp. For log construction and certain other forms of building the log is used whole, occasionally with its sides trimmed slightly flat with an axe. Pine has a longer lifespan if it is split in this way along two sides, because the hardness and amount of resin increases towards the centre of the trunk. Spruce should not be chopped along its sides, because the outside wood is stronger and heavier than the wood in the middle of the tree.

The oldest way of splitting a trunk is by cleaving through the core of the tree. The halves can be used as logs almost as they are, or they can be trimmed to a rectangular cross-section. They can otherwise be cleft radially, giving planks or 'shakes' with a slightly triangular profile. In technical terms, cutting timber trunks radially (in towards the centre) gives the most stable timber sections; however it is more time consuming and is seldom done in modern processes.

With the invention of the vertically adjustable saw during the sixteenth century, splitting timber by saw became the dominant technique. This method was particularly effective for cutting logs into panelling. For the last couple of centuries, the even more efficient circular saw has been used. For this method, there has to be a rotational force, usually produced by electricity. Rotational energy can also be produced directly by local wind or water turbines, as was the case in most former timber mills. In this way, the loss of energy in conversion to and transport of electricity is eliminated, and energy consumption can be strongly reduced. One should note that sawmills create a lot of dust in the working environment. Dust from western red cedar contains allergenic thujaplicins, and dust from oak and beech is carcinogenic.

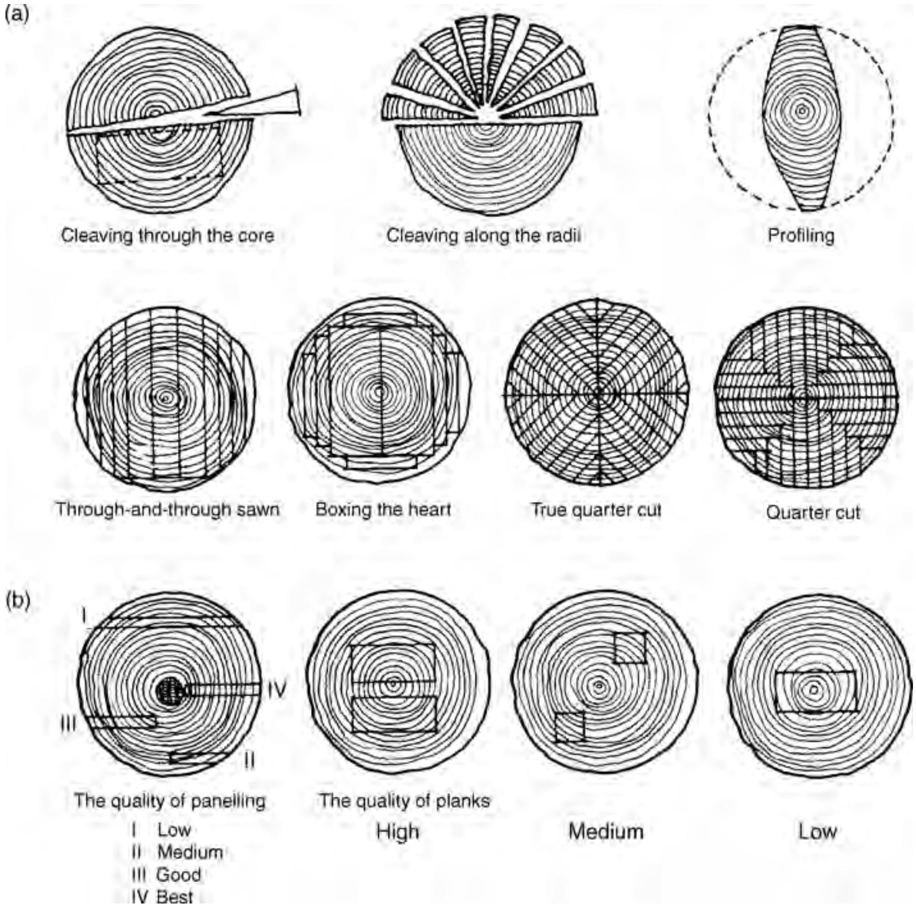
There are different techniques of sawing logs: sawing through and through, boxing the heart, true quarter cutting and quarter cutting (see Figure 10.4). Boxing the heart works well with the circular saw and is almost the only method used today.

The wedge is more sensitive with wood than the axe, and the axe is more sensitive than the saw. By using a wedge, the cells are kept whole when the wood is split. Saws cut through the cell walls. This is critical for the timber's absorption of water, which in turn governs the risk of attack by mould or insects. In spruce, which when whole has an impermeable membrane between the pores, this is particularly important.

Timber from deciduous trees often has high inner tensions. To avoid twisting in the sawn timber, it is preferable to keep to smaller dimensions. On average, a sawmill will convert about half of a typical trunk to construction lumber, whilst the rest is by-products and waste, often going to production of paper, energy or chemicals.

Drying. Some researchers say that the drying routines for freshly sawn timber are more important for its durability than the time of felling (Raknes, 1987).

In order to use sawn timber, 70–90% of the original moisture must be dried out, depending upon the end use. The sawn timber is stacked horizontally with plenty of air movement around it, and is dried under pressure. The stack can be placed outdoors or in special drying rooms. The outdoor method is more reliable for drying winter-felled trees during spring, as artificial drying produces some

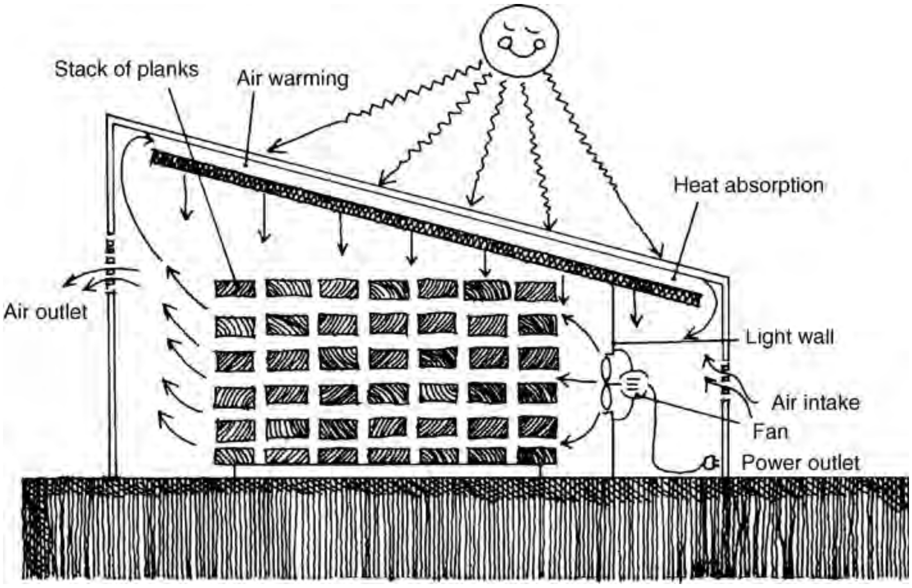


10.4

(a) Different methods of dividing up timber; (b) Qualities of panelling and planks.

problems. Certain types of mould tolerate the temperatures used in this technique, and develop quickly on the surface of the wood during drying, emitting spores that can cause allergies. It has also been noted that the easily soluble sugars that usually evaporate during the slow drying process are still present in artificially dried timber, and become a perfect breeding ground for mould. It is also possible that the natural resins in the timber do not harden properly. This could be, for example, why there often are considerable emissions of natural formaldehyde in buildings made purely of timber. Formaldehyde is an unwelcome substance in an indoor climate, and can cause irritation in the ears, nose and throat, allergies, etc. Another reason for drying timber outside is the lower energy consumption, which for an ordinary load of timber rises by 300% when dried artificially.

Drying outside is best carried out in the spring. The number of months required for drying can be roughly estimated by multiplying the thickness of the timber in centimetres with 3.2 for spruce and 4.5 for pine. Normal planks take about three months, deciduous trees take longer. When building with logs it is best to fell, notch and use the timber while it is still moist. Logs with large dimensions have a long drying time – it can take years. A log building will therefore shrink between 5 and 10 cm on each floor. When the moisture content has decreased to 15–20%, windows and panelling can be installed.



10.5

Solar drying of timber.

Source: Hall, 1981.

10.2.2 The durability of timber

All timber breaks down eventually (Table 10.9). This can happen either through oxidization or through reaction with micro-organisms. These processes of deterioration usually work together. Timber that is submerged in water is more durable because of the lower availability of oxygen; in swamps, timber can lie for thousands of years

Table 10.9 *Durability of timber*

Species	*Always dry (years)*	*Sheltered outside (years)*	*Unsheltered outside (years)*	*In contact with earth (years)*	*Underwater (years)*
Ash	300–800	30–100	15–60	Less than 5	Less than 20
Aspen	–	Low	–	Low	High
Beech	300–800	5–100	10–60	5	More than 300
Birch	500	3–40	3–40	Less than 5	20
Elm	1500	80–180	6–100	5–10	More than 500
Juniper	–	More than 100	100	–	–
Larch	1800	90–150	40–90	9–10	More than 1500
Maple	–	–	–	Less than 5	Less than 20
Oak	300–800	100–200	50–120	15–20	More than 500
Pine	120–1000	90–120	40–85	7–8	500
Poplar	500	3–40	3–40	Less than 5	–
Spruce	120–900	50–75	40–70	3–4	50–100
Willow	600	5–40	5–30	–	–

without deteriorating. Timber seems to be resistant to aggressive air pollution – as evidence of such damage occurring in timber has never been found.

Timber thus endures as long as it is not attacked by fire, insects or mould. The oldest-known timber building in existence is the Horiuji Temple in Japan, which was built of cypress in 607 AD. There are also completely intact timber beams in the 2000-year-old ruins of Pompeii. Norwegian stave churches are up to 900-years-old.

However, some factors are now beginning to threaten timber's reputation. The extensive use of artificial fertilizers is probably reducing its durability, since the fast growth of cells produces a spongier, more porous timber. Fast-growing species were introduced in the 1950s and have proven to yield lower quality timber. These conditions also led to a greater need to impregnate timber with chemicals, see Chapter 19.

10.2.3 Recycling

The longer a particular wood fibre is used, the longer those carbon atoms will stay out of the atmosphere. One very important reason for extending the lifetime of timber products is to maintain the binding of carbon that they represent. This is achieved, in part, by ensuring the preservation of timber elements as long as possible through effective protection against damp and other forces of decay. In addition, their recycling should be optimized.

The re-use of logs – in parts or as a whole – has traditionally been ubiquitous in most of Scandinavia. Both log construction and timber frame construction are building techniques where the components can be easily dismantled and re-erected without any waste. The Japanese have developed a whole series of techniques for timber joints without glue, the most well-known being the so-called 'timber locks'. Most structures in the twentieth century have been based upon less flexible principles; gluing and nailing have been the dominant methods of jointing.

Pure wood waste can be ground and recycled as raw material for various building boards, such as particle boards and oriented strand boards. It can also be energy recycled to good effect. However, glues, surface treatments and impregnating agents often turn these products into hazardous waste. Energy recovery then demands combustion in special ovens with high quality flue gas cleaning. Chemical impregnation requires combustion in very high temperature furnaces, such as at cement factories.

By using the available forms of re-use and recycling, it is estimated that the useful service life of pine could be extended from about 75 years to more than 350 years (Fraanje, 1997). In central Europe and the USA, comprehensive timber recycling is now developing. Old timber has the advantage that, since it is 'dead', it does not twist, and therefore provides high quality material for floors, for example. In Belgium and France, old quality timber costs about 25 to 50% of the price of new timber, while in Holland old timber costs up to 75% of the price of new.

10.3 GRASSES AND OTHER SMALL PLANTS

Plants provide structure, fibre and a range of extracts with wide applications in construction (Table 10.10). Plants – mainly of the grass species – produce straw and fibres that often have a high cellulose and air content, making them strong, durable and well-suited for use in thermal insulation, as reinforcing and fillers in

Table 10.10 *The use of grasses in buildings*

Species	*Part used*	*Areas of use*	*Climatic limits*
Cultivated plants:			
Barley (*Hordeum*)	Stalk	Roofing	Cool temperate
Coconut (*Cocos nucitera*)	Nutshell	Thermal insulation, sealing joints	Subtropical
Coriander (*Coriandrum sativum*)	Seed	Bioplastics	Warm temperate
Cotton (*Gossypium*)	Stalk	Building boards, thermal insulation	Warm temperate
Elephant grass (*Miscanthis sinensis gigantheus*)	Stalk	Building boards, thermal insulation, reinforcement in earth and concretes	Warm temperate
Flax (*Linium*)	Stalk	Roofing, external cladding, building boards, thermal insulation, textiles, reinforcement in earth and concretes, rope and woven wallpaper	Cool temperate
	Seed	Oil treatment, paint, putty	
Hemp (*Cannabis sativa*)	Stalk	Building boards, reinforcement in concretes, thermal insulation, textiles	Cool temperate
	Seed	Paints, bioplastics	
Jute (*Corchorus capsularis*)	Stalk	Sealing joints	Subtropical
Maize (*Zea mays*)	Seed	Adhesives, bioplastics	Warm temperate
Oats (*Avena*)	Stalk	Roofing	Cool temperate
Potato (*Solanum tuberosum*)	Seed	Adhesives, bioplastics	Cool temperate
Rice (*Oryza sativa*)	Stalk	Building boards	Warm temperate
	Seed	Bioplastics	
Rye (*Secale cereale*)	Stalk	Roofing, external cladding, building boards, thermal insulation, reinforcement in earth and concrete, woven wallpaper	Cool temperate
	Seed	Adhesives, paints	
Soybean (*Glycine max*)	Seed	Paints, adhesives, bioplastics	Warm temperate
Sugar-cane (*Saccharum officinarum*)	Stalk	Building boards, bioplastics	Subtropical
Wheat (*Triticum*)	Stalk	Roofing, external cladding, building boards, thermal insulation, reinforcement in earth and concrete	Cool temperate
	Seed	Bioplastics	

Table 10.10 *(Continued)*

Wild plants:			
Alpine Hawkbeard (*Crepis nana*)	Seed	Bioplastics	Cool temperate
Bracken, common (*Pteridium aquilinum*)	The whole plant	Roofing	Cool temperate
Cat-tail (*Typha*)	Seed	Thermal insulation	Cool temperate
Eelgrass (*Zostera marina*)	Leaves	Roofing, external cladding, thermal insulation, building boards	Boreal
Greater pond sedge (*Care riparia*)	Stalk	Roofing	Cool temperate
Marram grass (*Ammophila areniaria*)	Straw	Roofing	Cool temperate
Moss (*Hylocomium splendens*) and (*Rhytriadiadelphus squarrosum*)	The whole plant	Sealing of joints, thermal insulation, building boards	Cool temperate
Reed (*Phragmites communis*)	Stalk	Roofing, reinforcement in stucco work and render, insulation matting, concrete reinforcement	Cool temperate
Ribbon grass (*Phalaris arundinacea*)	Stalk	Roofing, reinforcement in stucco work and render, insulation matting, concrete reinforcement	Cool temperate
Scotch heather (*Calluna vulgaris*)	Whole plant	Roofing, thermal insulation	Cool temperate
Stinging nettle (*Urtica*)	Stalk	Thermal insulation, building boards, textiles	Cool temperate

Note: Many of the wild plants can be cultivated; e.g. stinging nettle, reeds and cat-tail.

various building boards. Species such as rye, wheat and flax contain natural glues and can be pressed into building sheets without additives. Cleaned plant fibres of flax, hemp and nettles can be woven into linen, carpets, wall coverings and ropes. Starch and plant oils form the basis for many surface treatments, paints and bioplastics.

Mosses have long been used to seal joints between construction parts, such as between the logs in log constructions. *Sphagnum* moss contains small quantities of natural phenol compounds that impregnate the material.

The main constituent of peat is decomposed plant matter. Dried peat can be used in building sheets and as thermal insulation.

Grasses and other small plants represent a large potential resource. A century or so of technological and industrial growth has led to most of these being abandoned in building, since they have been perceived as ineffective and not susceptible to industrialization. This is changing, given today's new focus on ecological qualities; some also have superior technical properties. On the other hand, genetically modified plants, such as maize and soya, are spreading rapidly and need to be considered carefully.

BAMBOO

In the world's tropical and subtropical regions one of the most important plant material of all is bamboo. Bamboo may be harvested from the wild or else semi-cultivated. It is very resilient, resistant and almost everlasting. Some 1250 species and 1500 traditional applications have been identified, many of them within building construction (Follett, 2003). Bamboo is extensively used as a load bearing structure, roofing and flooring in the vernacular architecture of many cultures. One billion people worldwide live in bamboo houses. In many countries one now sees research projects and efforts to find new ways to use bamboo in improved traditional construction. Thick bamboo stems naturally take quite some years to grow, so sustainability will be an issue if the local resource is over-exploited.

10.3.1 Cultivating and harvesting

Most cultivated plant products used in construction are by-products from the production of grain. Production of grain is often based on the extensive use of synthetic fertilizers and pesticides. Plants that have a high resistance to moulds and insect attack include hemp, elephant grass and linseed. Nevertheless, in linseed cultivation it is common to use 0.7 kg of pesticides per hectare – of which about 20% is lost to the atmosphere (Lippiatt, 2007). Alternative methods are possible, including the various types of organic farming, though in general they give lower yields. Ripe grain is usually harvested in late summer. Cutting of wheat and rye to be used for roof covering must be carried out without breaking or splitting the stalks.

Many of the useful, wild species grow in water – reeds, ribbon grass and pond sedge. These plants are perennial, sprouting in spring, growing slowly through the summer and withering during winter. On a land area of 1000 m^2 0.5–3 tons of material can be produced. Harvesting either by boat or from the ice occurs in winter. Some of the species can be described as semi-cultivated, since the areas around are cleared to maintain good conditions for growth, and harvesting is done selectively. Some 'wild' plants are fully cultivated, for example nettles, which can give yields off almost 5 kg of biomass per square metre.

Moss grows ten times more than forests in volume per unit area. When harvesting moss, care must be taken not to destroy its system of pores. The best technical quality is achieved if it is pulled up in pieces.

Harvesting peat is best done during the summer when peat bogs are at their driest. Summers with high rainfall can cause problems during harvesting as well as in the quality of the final product. Whereas peat was formerly worked with a special range of manual techniques and tools, there are now large machines that shave 3–5 cm off the surface of the peat, cut it into blocks, stack it and dry it.

When large areas with wild species are harvested the local ecology of the area must be handled with particular care, especially species such as moss and peat. Marshes are very sensitive ecosystems.

10.3.2 Preparation

Most of the smaller plants must have leaves, seeds and flowers removed before being used as roof covering, thermal insulation, etc. Extraction of fibre from plants such as flax, stinging nettles and hemp is carried out by retting on the ground, left to mould, bacteria, sun and rain for two to three weeks, until the fibres loosen and can be collected for the further final cleaning process.

Thereafter, fibres are woven, needle-punched or glued into mats or sheets, sometimes also used as loose fill. The seeds are often pressed for oil. Pressing may be cold or with heat to extract more. Additives are often used in these processes, either to facilitate the process or to improve the properties of the final product. These include fungicides, adhesives, fire retardants and water repellents. Many of these may be suspect chemicals.

10.4 BUILDING CHEMICALS FROM PLANTS

Plants are the source of many chemicals used in building. The active ingredients may be extracted using water, alcohols or weak alkaline solutions. They may amount to 5 to 10% of the dry mass of the biomass material. For the most part production takes place in large-scale industrial units. In the late 1980s, however, the concept of smaller 'bio-refineries' was introduced; the concept being to process optimally all the constituents of a given crop in decentralized units near the source of cultivation (Ienica).

Methanol (CH_3OH) is the simplest form of alcohol. It is a main constituent of wood vinegar, which deciduous trees – such as beech, poplar and birch – contain in large quantities. Today, methanol is principally produced from natural gas. It is widely used as a solvent, including in paints and cellulose based varnishes.

Methanol forms a base for the production of formaldehyde, used extensively in synthetic glues and some thermosetting plastics. Methanol can also be used to produce ethylene and propylene, the main building blocks for most conventional plastics.

Acetic acid (CH_3COOH) can also be manufactured from wood vinegar but is mostly produced from fossil oils today. It has a disinfectant effect on timber that is attacked by mould, and is also important in the production of several bio-plastics.

Terpenes. Turpentine ($C_{10}H_{16}$) is distilled from wood tar, mostly from coniferous trees. Limonene is extracted from lemons. Both are widely used as solvents, especially in paints.

Fatty acids are produced from plants such as pine, linseed and soya. They are used in alkyd oil paints and varnishes as drying agents. They can themselves also be the binding agents in these products. Some, including butyric acid $CH_3(CH_2)_2COOH$, are used further in producing bioplastics. Soaps, used for treatment and saturation of wood, are derived by reacting fatty acids with lye (potash) in a process known as saponification.

Starch $(C_6H_{10}O_5)n$ is a main constituent of potatoes, wheat, rice, maize, etc., and is a major ingredient in many glues used for wallpapers and paper laminates. Starch is also used as binding agent in paints and is a widely used base for bioplastics.

Lignin is a complex chemical compound most commonly derived from wood, where its function is to fix cellulose fibres and protect against mould. The cellulose industry normally produces quite large quantities of lignin as a by-product. Much of this is combusted for energy production. In the construction industry lignin is sometimes used as glue in wood fibre boards, and as additive in gypsum boards and concrete admixtures. It can be used for production of bioplastics, and insulation products of expanded (foamed) lignin are also under development.

Laccases are copper-containing enzymes that are found in many plants, and in fungi and micro-organisms. Laccase is used to activate lignin in plant-based boards and insulation products in order to bind them without the need to add glues.

Silicates. Siliceous plants contain large quantities of active silicates that react very strongly with lime, and the ash left over after burning the plants can be used as pozzolana in cements. Common horsetail (*Equisetum arvense*) is particularly rich in silica.

Potash. Deciduous trees contain a particularly high amount of potash K_2CO_3, the main constituent of the ash left over after timber has been burnt. Potash is an important ingredient in the production of glass. These days, however, it is almost exclusively produced industrially from potassium chloride.

10.5 CELLULOSE

Cellulose $(C_6H_{10}O_5)_n$ can be produced from peat, straw or timber; the majority comes from timber. By weight cellulose is 44% carbon, 6.2% hydrogen and 49.4% oxygen.

In the sulphite chemical process of the paper industry, timber is ground and cooked under pressure with a solution of calcium hydrogen-sulphite, $Ca(HSO_3)_2$, releasing the lignin. The pure cellulose is then washed and often bleached. To produce paper glue and filler substances such as powdered heavy spar, kaolin or talcum are mixed in. Omitting the glue will produce more brittle, porous paper.

Cellulose fibres are often used in insulation materials, either as virgin fibres or recycled. They are also used as reinforcement in cement-based building boards. Paper products are found in many building products, from building boards to wallpapers.

Further processing of cellulose leads to cellulose glue, cellulose varnish, viscose, rayon, etc. Other chemicals are often added in these processes, e.g. acetic acid and methanol. Cellulose acetobutyrate (CAB) and cellulose propionate (CAP) are plastics made by processing cellulose with acetic acid and butyric acid. These materials are as clear as glass and can be used to produce roof lights. Cellulose-based plastics are well suited for being mixed with plant fibres into biocomposites (Mohanty *et al.*, 2005).

The cellulose industry consumes large quantities of water and causes high pollution levels. The cooking process leaves a substantial amount of lye as a by-product. This contains different organic process chemicals, of which a few are recycled; the rest are released into rivers or lakes near the factory. If the cellulose is bleached with chlorine, pollution increases drastically. Organic chlorine substances can accumulate in the nutrient chain with toxic effects. Alternatives are bleaching paper with oxygen or hydrogen peroxide.

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11 Materials of animal origin

Animals are mainly herbivores. Certain species, such as cows, can digest carbohydrate cellulose and change it into nutrients. Humans are mainly dependent on an intake of carbohydrates in the form of sugar and starch, but also need protein, carbohydrate, vitamins, minerals, etc.

Humans and animals depend entirely on air for respiration. Oxygen enriches the blood and makes the body capable of burning food in an exothermic reaction releasing heat, approximately 80–150 W for an adult human being, depending upon the level of activity.

Associated with the very ancient constructions is the use of animal products such as hides and sinews for fastening and cladding. There was also the bizarre use of animal (mammoth) bones as a structural material on the steppes of Eastern and Northern Europe. Animal glue is the oldest type of glue known, and was used in ancient Egypt. In later times, animal products have played only a minor role, such as blood and cow manure added as binding agents in earth constructions and wall renderings.

Yet products from the animal world still have a limited use in modern building. Sheep's wool is common in carpets, wallpapers and building paper products. Wool of lower quality, which would otherwise be wasted, can be used for insulation and joint sealing. The substance keratin, which strengthens plant fibre products, can be extracted from wool as well as from feathers (Kawahara *et al.*, 2004). Beeswax has become a popular substance for treating timber surfaces.

Protein substances extracted from milk, blood or tissues are still used as binding agents for paint and glue. Traditional animal glue is produced by boiling skin and bone to a brown substance. When it is cleaned, gelatine, which is also a useful base for bioplastics, is obtained. Casein glue is made from milk casein, produced from curdled milk by adding rennet. Casein contains more than 20 different amino acids and is a very complex chemical substance, but has no binding power in itself. Lime or other alkalis must be added and the mixture is dissolved in water, see page 263. Casein plastic CS is produced from milk casein by heating the casein molecules with formaldehyde under pressure. This plastic, also called synthetic bone, is sometimes used for door handles.

Adding whey can improve the fire resistance of insulation materials by producing nitrogen under intense heat. When lactic sugar ferments,

Table 11.1 *Building materials from the animal kingdom*

Species	*Part used*	*Areas of use*
Mussels	Shell	Aggregate in concretes and mortars, thermal insulation, capillary barriers
Coral	Mineral part	Building blocks, structures
Bees	Wax	Surface treatment of wood
	Skeleton	Bioplastics (via *chitin*)
Shellfish	Skeleton	Bioplastics (via *chitin*)
Fish	Oil	Binder in paint and adhesives
Birds	Down	Strengthener in products of natural fibres (*keratin*)
	Egg	Binder in paint and adhesives
Hoofed animals	Wool (sheep/goat)	Textiles, sheeting, joint sealing around doors and windows, thermal insulation, strengthener in products of natural fibres (*keratin*)
	Hair (horse, pig, cow)	Reinforcement in clay plasters and mortars.
	Hides and skins	Internal cladding, floor covering, binder in paint and adhesives (*protein*)
	Bone tissue	Binder in paint and adhesives (*protein*), black pigment in paints (*ash*)
	Blood	Binder in paint and adhesives (*protein*), water repellant and stabilizer in earth constructions
	Milk	Binder in paint, adhesives and fillers (*casein*), flame retarder (*whey*), biocide (*lactic acid*), bioplastics (*casein, lactic acid*)
	Manure	Stabilizer in earth constructions

lactic acid ($C_2H_4OHCOOH$), which is a mild disinfectant, is produced. It can also be polymerized to form one of the leading bioplastics, polylactic acid PLA.

Coral is already widely used as a building material in the Maldives and similar island communities. In the tropical oceans, a future can be envisaged in which living corals (which depend upon warm water for quick growth) could be used in manufacturing tailored building components. However, this has considerable moral implications – as toxins might have to be used to hinder growth and produce the right forms and dimensions.

Various shell materials are also of interest. The large quantities of shells discarded from mussel farms and similar production industries seem to be promising as an aggregate in mortars (Yoon *et al.*, 2004). Roughly crushed mussel shells have also been used as heat insulation and capillary break under floors. Chitin, found in the skeletal tissue of marine crustaceans – shrimp, lobster and other shellfish – is also expected to become a future base for bioplastics (Stevens, 2002).

11.1

The woollen fibres of a sheep can be used as the main ingredient in paper, sealing strips and thermal insulation. The bones, milk and blood can form the basic materials for bioplastics and binders in glues and paints.

THE PURPLE SNAIL

The purple snail, Purpur lapillus, lives along most European coasts (Figure 11.2). It is so called because it has a gland containing a coloured juice. The juice smells bad, but after painting with it in full sunlight, a purple colour appears after ten minutes that is clear,

11.2

The deserted shell of purple snails.

beautiful, durable and does not fade. A huge amount of snails are needed for the smallest amount of decoration. The development of this colour technique occurred in the eastern parts of the Mediterranean after the Phoenicians settled, about 5000 years ago. In Asia, the purple painters had their own workshops at the royal courts, and purple became the colour of the rulers. The snail was worth more than silver and gold, but with the rise and fall of the Mediterranean empires almost the whole population of snails disappeared. Today the purple snail is no longer considered a resource. The surviving snails are threatened by pollution from organic tin compounds used in some PVC products and the impregnation of timber.

In principles, the use of animal products has similar environmental impacts to the use of plant products, both being primarily renewable – but conditionally renewable – resources. Climate change may seriously affect their renewability in some cases. For example, more acidic oceans will change the conditions for lime formation in corals and shells.

The amount of energy used for production of most animal products is relatively small; durability is usually good and the materials are easily decomposed assuming no problematic additives. The level of pollution is low. An exception is products from sheep and cows. Where sheep and cows mainly graze on chemically fertilized pastures, this implies quite high energy use as well as the release of eutrophicating substances. Their digestive tracts will also produce and release large amounts of the highly potent greenhouse gas methane throughout their lifetimes. It is thus not environmentally acceptable to raise these animals primarily for the production of building materials. Normally, however, their primary purpose will be to produce meat and milk. Waste wool and similar by-products will therefore not be ‘charged’ with the climate emissions.

Protein substances can cause allergies in sensitive people. These substances can be released into the air when moistened, and internal use of such paints, glue and fillers should be limited to dry places. It has also been noted that casein mixed with materials containing cement, e.g. in fillers used to level floors, can develop ammonia fumes.

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12 Industrial by-products

Industrial processes often release by-products during the refining of raw materials, combustion, filtering, cleaning of effluents, etc. Materials such as smelting slag and combustion ash are also by-products.

By-products can have several interesting properties when considered as raw materials:

- They are abundant without necessarily being in demand.
- Chemically speaking, they can be relatively pure in composition.
- It is usually difficult to dispose of them.
- Other raw materials are saved by using them.
- They will often cause environmental pollution if released to air, earth or water.

The planned use of industrial by-products is a relatively new phenomenon in building, and is now primarily a consideration of substances, which can be used as constituents in cement and concrete products (Table 12.1). Increased use of by-products, which have properties similar to pozzolana, for example, will drastically reduce energy consumption within the cement industry, as well as save other raw material resources.

12.1 INDUSTRIAL GYPSUM

It is necessary to differentiate between '*power station*' gypsum, which is released in desulphurizing plants at power stations using coal, and *phosphorous* gypsum from the production of artificial fertilizers. Power station gypsum has similar technical properties to natural gypsum and is appropriate as a raw material for both plasterboard and Portland cement. Phosphorous gypsum has a higher likelihood of unwanted constituents because of the raw material used. This will often include radioactive substances. Gypsum is also a by-product of other industries, such as in the production of phosphoric acid and titanium oxide, but often contains large quantities of unwanted materials such as heavy metals.

12.2 SULPHUR

Sulphur is a by-product in industries where gas and oil are burned. The quantities are large.

Table 12.1 *Industrial by-products in the building industry*

By-product	*Orgin*	*Areas of use*
Industrial gypsum	Zinc works, oil- and coal-fired power station, brick production, production of artificial fertilizer	Plasterboard; plasters; Portland cement
Sulphur	Oil- and gas-fired power station, oil refineries	Sulphur-based render; sulphur-based concrete; paper production
Silicate dust	Production of ferro-silica and silicon dioxide	Reinforcement in concrete products; pozzolana
Blast furnace slag	Iron foundries	Pozzolana; thermal insulation (slag wool)
Fly ash	Coal-, oil- and gasfired power stations	Pozzolana
Fossil meal	Oil refineries	Pozzolana; thermal insulating aggregate in render and concrete
Fibreous cellulose sludge	Cellulose production	Fibre composites

Sulphur has been used for a long time in the building industry to set iron in concrete, e.g. for setting banisters in a staircase. At the end of the nineteenth century the first sulphur concrete blocks came onto the market. Sulphur is also an important raw material in the production of ammonium sulphate and aluminium sulphate. Ammonium sulphate is a flame retardant and aluminium sulphate a fungicide much used in plant-based insulation materials.

Sulphur has a melting point of a little less than 120 °C, and when melted binds well with many different materials. It can replace other materials used in casting such as Portland cement. Sulphur concrete is waterproof and resistant to salts and acids.

As the temperature for working molten sulphur is low there is probably little risk of the emission of hazardous doses of either hydrogen sulphide or sulphur dioxide, though even the slightest emission of the former gives a strong unpleasant smell. The workplace should be well ventilated. Sulphur burns at 245 °C, and large quantities of sulphur dioxide are emitted. Under normal circumstances there is little risk of the material igniting.

12.3 SILICATE DUST

Silica dust, also called micro silica, is removed from smoke when ferro-silica and silicon dioxide, used in steel alloys and the chemical industry, are produced. Silica dust is mainly composed of spherical glass particles. It does not react with lime and is a highly rated concrete reinforcement. It can, for example, replace asbestos. Silica dust is relatively new on the market, but is already used in products such as light concrete blocks, concrete roof tiles and cement sheeting.

12.4 BLAST FURNACE SLAG

Blast furnace slag is produced in large quantities at works processing iron ore. The slag is basically the remains of the ore, lime and coke from the furnaces. This is considered to be a usable pozzolana and can be used in mixtures with lime and Portland cement, see pages 94-95. Before it can be used it has to go through a process of quenching and granulating.

It is also possible to produce an expanded 'slag wool' which can be used as thermal insulation in the same way as mineral wool. The constituents of blast furnace slag increase the level of radioactive radon in a building, though the levels are generally quite negligible.

12.5 FLY ASH

Fly ash reacts strongly with lime and is used as a pozzolana in Portland cement, see page 94-95. It is a waste product in very large quantities at power stations that use fossil fuels. It contains small amounts of poisonous beryllium and easily soluble sulphates that can seep into and pollute a groundwater system if they are dumped. Fly ash from waste burning processes should not be used because it will probably contain larger amounts of heavy metals.

12.6 FOSSIL MEAL

Oil refineries that use oil from porous rock formations on the seabed will produce fossil meal as a by-product. This can be used as thermal improvement for mortars and is also a good pozzolana.

12.7 FIBROUS CELLULOSE SLUDGE

The paper and pulp industry produces large volumes of waste sludge, primarily as a result of processes such as de-inking wastepaper and wastewater treatments. This sludge, though it is often just sent to landfills, is rich in fibre. Even if fibre lengths are shorter than in normal cellulose fibre, it has been shown that it can replace 20 to 50% of the fibre reinforcing in fibre-cement composites without reducing the resultant product strength (Modolo *et al.*, 2007). Sludge fibres can therefore probably also be useful in other composite materials, for example with bioplastics used as binder.

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PART 3 THE CONSTRUCTION OF A SEA-IRON-FLOWER: BUILDING MATERIALS

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13 Structural materials

A building structure usually consists of the following parts:

- *The foundation*: transfers the weight of the building and other loads to the ground, usually below ground level. In swamps and other areas with no loadbearing capacity, the load must be spread onto rafts or piles going down to a solid base.
- *The wall structure*: carries the floor and roof and resists wind loads. The walls can be replaced by freestanding columns.
- *The floor structure*: carries the weight of the people in the building and other loads such as furniture and machinery.
- *The roof structure*: carries the weight of the roof and resists wind and snow loads.

In theory, these elements can be separated, but in practice the different functions usually have no clear boundaries. The structural elements have an intricate interaction in relation to the bracing of a building; for example, a particular wall structure can be dependent upon a specific floor structure for its structural integrity. Many parts also fulfil multiple building needs, such as thermal insulation, heat storage and sound proofing.

Structural materials are principally defined in terms of bending strength, compressive strength, tensile strength and elasticity. These properties give an idea of the ability of the material to cope with different forces. How this happens depends upon the design and dimension of the structure. A steel cable has its strength in its capacity to take up tensile forces – stretching – such as in a suspension bridge. A brick, however, almost entirely lacks any such stretching properties and must be used in a way that uses its compressive strength. Structures such as in brick that are in a state of static equilibrium tend to have a longer lifespan than those exposed to tensile loads, which in the long run are subjected to material fatigue.

The proportion of structural materials in a building may be 70 to 90% of the weight; a timber and steel building has the lowest percentage, and brick and concrete have the highest.

Structural materials usually provide less negative environmental effects per unit of weight than other building materials. They are usually based on renewable resources such as timber, or on materials with rich resource reserves such as clay, lime or stone. Production is preferably local or regional. The amount of energy consumed in production and

Table 13.1 *Structural materials in foundation, wall, floor and roof*

Material	*Foundation*	*Wall*	*Floor*	*Roof*
Steel	Gu	Gu	Gu	Gu
Aluminium	Nu	Lu	Lu	Lu
Concretes with air- curing binder		Nu	Nu	Nu
Concretes with hydraulic cement	Gu	Gu	Gu	Gu
Stone	Lu	Lu		
Bricks, well-fired	Lu	Gu	Lu[1]	Lu[1]
Bricks, low-fired		Lu	Lu[1]	Lu[1]
Compressed earth		Lu	Lu[2]	Lu[2]
Softwood	Lu[3]	Gu	Gu	Gu
Hardwood	Lu[4]	Lu	Lu	Lu
Turf		Nu		

Empty spaces indicate not relevant.
Abbreviations: Gu: In general use; Lu: In limited use; Nu: Not in use.
[1] As special structural elements or as vaults.
[2] As vaults.
[3] Pine below the water table.
[4] Alder below the water table.

transport is approximately 30 to 40% of the complete house. Pollution due to greenhouse gases and acidifying sulphur dioxide will vary from 35 to 70%. The level of environmental poisons will probably be lower, and as waste products the majority of structural materials are not a problem. As these materials are relatively simple combinations of elements with large dimensions, they are well suited for recycling, but the type and quantity of binders and the size of the units are decisive factors.

Despite their relatively good environmental profile, the choice of structural materials is a decisive factor in a building's environmental profile because of their large volume and weight. If concrete and bricks are substituted by wood constructions, the emissions of greenhouse gases in material production are reduced by approximately 1 ton of CO_2-equivalents per ton of wood used (Kram *et al.*, 2001). This coefficient is based on a weight substitution ratio of concrete and bricks by wood of 5:1 to 10:1. If such substitution were applied widely in Europe, greenhouse gas reductions could be achieved corresponding to Norway's annual emissions of 50 million tons of CO_2-equivalents. In addition, the timber should be credited as medium term storage of carbon corresponding to 0.8–0.9 tons of CO_2 per ton of wood used (50 years). For Western Europe alone this would be of the order of 30–40 million tons of CO_2. However, as an important part of the calculations the role of operational energy use should also be taken into consideration. Here constructions based on brick and concrete will constitute additional thermal mass, which can reduce heating and cooling energy demand.

13.1 METAL STRUCTURES

13.1

Early use of cast iron in a London railway station.

Basic info is found in Chapter 6.

Metal structures are relatively new in the history of building. Despite this, they have, together with concrete, become the most common structural systems in large buildings over the past 100 years. In industrialized economies, metal structures have also dominated the market for transportable and temporary buildings. Metals may twist or melt during fires but they do not burn, and are strong and durable in relation to the amount of material used; and they are 'industrial' products.

Early structures in cast iron soon gave way to steel (Figure 13.1). Aluminium is used in light structures, but steel is without doubt the most common structural metal, and is used in foundations, walls, roof and floor structures.

The steel used in reinforcement of concrete is usually unalloyed and often recycled from scrap. This means that it corrodes easily. Steel used in columns and beams is very often galvanized. High quality steel is alloyed with small amounts of aluminium and titanium. The resulting material is particularly strong, and means that the amount of material used can be reduced by up to 50%.

Steel components are usually prefabricated in different cross-sections and as square hollow sections, round hollow sections or cables, put together to make different sorts of braced or unbraced framework structures. It is common practice to weld the components together on site. Steel components can also be fixed together mechanically, with or without the use of bolts. This considerably increases ease of recycling.

The production of metal products causes high levels of environmental pollution and emissions as well as being energy intensive. Once installed there are no significant emissions. As with many other materials, one must remember that possible additives may change this picture. For example, surface treatment such as in particular the fireproof coatings required in many steel structures may contain highly toxic substances.

Metal structures can affect the indoor climate by picking up vagrant electrical currents from electrical installations and distributing them around the building. This can result in changes or increases in the electromagnetic fields in the building, which can affect health by inducing sickness and fatigue. When dumping metals, a certain level of seepage of metal ions to the soil and ground water must be assumed.

Both aluminium and steel components can be recycled. It has also proved profitable to re-use steel components in their original state (Addis, 2006). Steel is also widely used in foundation systems such as circular piles, sheet pile walls or tubular elements. Screw piles are significantly easier to withdraw subsequently and recycle (Figure 13.2).

In Denmark, the market value of well-preserved steel components from demolition has reached ten times the scrap value. Old railway lines have been used in the structure of office buildings in Sweden. When re-using metal structural elements, the risk of material fatigue has to be assessed.

13.2

Foundation with screw piling. When the building is demolished the screw piles can easily be unscrewed and re-used. Traditionally screw piling was much used for lighthouses on sandy shores.

Source: RW Able, ScrewFast Foundations Ltd.

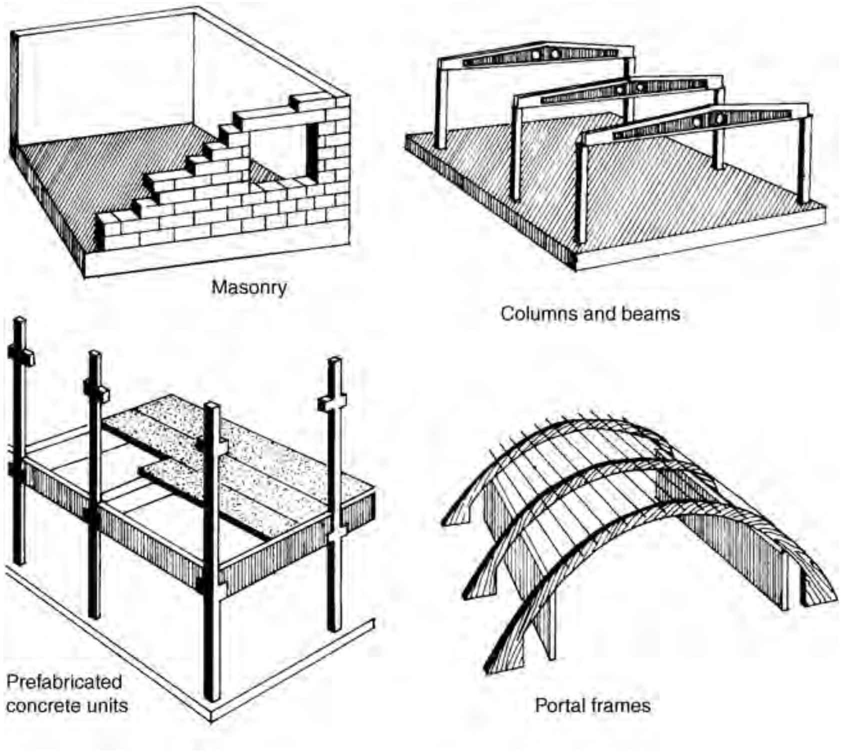
13.2 CONCRETE STRUCTURES

Basic info is found in Chapter 6.

Concrete is produced from cement, aggregates, water, plus occasional additives. It is cast on site in shuttering or prefabricated as blocks or larger units (Figures 13.3 and 13.5). Prefabricated components are very often produced with hollow centres to reduce weight or improve thermal insulation. With few exceptions steel reinforcement is used.

Concrete's most important properties are high compressive strength, fire resistance and thermal storage capacity.

Pure concrete structures are relatively rare in early building history, when cement was used mostly as a mortar to bind bricks or stones.



13.3
Prefabricated concrete construction systems.

Exceptions exist in the Roman Empire where the coffers in the ceiling vault of the Pantheon are cast in concrete using pumice as aggregate. In the 1930s, and again since the Second World War, the use of concrete in building became widespread. Today it is the leading building material for foundations, structural walls, roof and floor construction in larger buildings. It is also one of the main materials used in many other civil works such as dams, roads, bridges and retaining structures.

Concrete binders and, to a certain extent, reinforcements, are the constituents with the highest environmental impact. It is important to choose the most appropriate alternatives, at the same time reducing the proportion of these constituents.

13.2.1 The composition of concrete

Binders
Air-curing binders and hydraulic cements can be used. Among air-curing binders, slaked lime and gypsum are the most important ingredients. Hydraulic cements include lime and pozzolana mixtures and Portland cement, often with pozzolanas added. Another hydraulic alternative is geopolymeric cement which is manufactured without lime. Sulphur, see page 185, is a binder in a group of its own because it cures when cooling, having passed through a melting phase.

Cements based on lime, including Portland, which is by far the most common type, cause very high emissions of carbon dioxide during production. If lime based ingredients are replaced by pozzolanas this can be somewhat reduced. Some of the carbon dioxide emitted during production will, during the building's lifetime, be reabsorbed through the process known as carbonatation (Fossdal, 2003). Geopolymeric and sulphur cements have low associated climate emissions.

During construction, contact with lime products can cause serious damage to the skin and eyes, so these products should be used with care. Portland cement contains chrome that can lead to a skin allergy, even though current products are usually neutralized, mostly with ferrous sulphate.

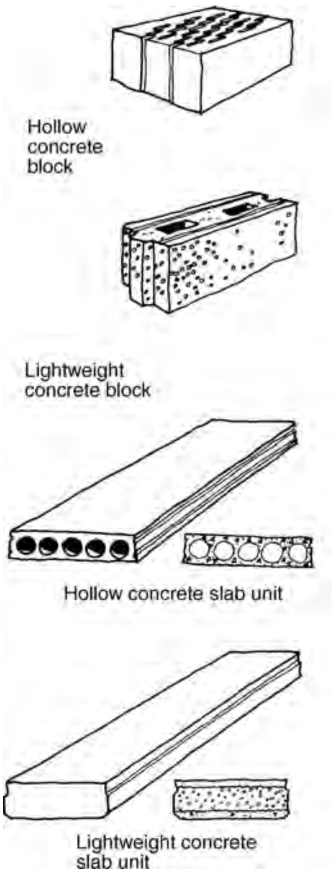
Pure mineral binders usually have no effect on the indoor climate. There can, however, be cement dust from untreated concrete surfaces. This can irritate the mucous membranes. Problems also occur if cement dust is left behind when a building is completed, for example in ventilation ducts. If the cement is not completely hydrated, due to insufficient watering, it is capable of reacting with other materials such as fillers with organic additives and plastic coatings.

As a waste product, Portland cement with fly ash releases soluble sulphurs into the environment.

Generally speaking lime cements and geopolymeric cements give the least environmental problems but they are slightly weaker than Portland cement.

Aggregates

In ordinary concrete the aggregates are divided into three groups: sand, gravel and crushed stone. In lightweight concrete there are also air-filled, thermally insulating aggregates which are discussed in Chapter 14 (See also summary in Table 13.3).



13.4

Standard concrete precast units for walls and floors.

13.5

Mortar free construction with concrete lightweight blocks.

Source: Maxit.

13.6

Mobile equipment for producing recycled aggregate.

Little attention has been paid to the fact that different types of crushed stone make different demands on the concrete mix. The decisive factor is the tensile strength, and paradoxically a low tensile strength is more favourable. Crushed stone with a tensile strength of 200 kp/cm^2 needs much less cement than that with an ultimate strength of 500 kp/cm^2. Up to 10% of the world's cement production could probably be saved if this was considered (Shadmon, 1983).

In places with no sand, gravel or crushed stone, several types of building waste that do not attack lime can be used. Clay tiles and clay bricks crushed to a size of 1–40 mm can be used, but the material must be of good quality. Brick waste cannot be used if it contains nitrate residue from artificial fertilizers, as this increases the decay rate of the concrete. Artificial fertilization of agricultural land became widespread in the 1950s and affects many sites where raw material for brick-making is extracted.

In many European countries, Portland cement-based concrete is now being recycled to some extent (Figure 13.6). The concrete is crushed back to normal aggregate size and can be used up to a certain proportion in new concrete, depending on the strength required; for example, in concrete slabs for foundations of small houses and parking blocks, where they can replace up to 20% of the gravel.

There have also been successful test projects using recycled glass as aggregate in concrete. This has also been shown to reduce the need for plasticizers. If the recycled glass is used in foamed form this creates a lightweight and thermally insulating concrete. Other industrial residues such as fly ash and some types of slag can also be used**.** Another experiment has been to solve a major waste problem by adding used car tyres in ground up form, a product named *Rubcrete* (Lu *et al.*, 2007).

In some countries where deposits of gravel and sand are scarce, sand is sometimes removed from beach zones and even from the sea.

Table 13.2 *Concrete mixes, their properties and areas of use*

Type	*Mixtures, parts by volume*	*Properties*	*Areas of use*
Lime sandstone	Lime 1; Quartz sand 9	Durable, sensitive to moisture/frost	Internal and external structures, cladding, moisture buffering
Lime concretes	Lime 1; Sand 2-4; Aggregate 4-6	Elastic, sensitive to moisture/frost	Internal structures, moisture buffering
Lime pozzolana concretes	Lime/pozzolana 3; Sand 1; Aggregate 2	Medium strength, elastic, resistant to moisture/frost	Internal and external structures
Gypsum concretes	Gypsum 1; Sand 1; Aggregate 2	Sensitive to moisture/frost	Internal structures, moisture buffering
Portland concretes	Cement 1; Sand 3-6; Aggregate 3-5	Strong, durable, not particularly elastic, resistant to moisture/frost	Internal and external structures, foundations
Portland-pozzolana concretes	Cement/pozzolana 1; Sand 3; Aggregate 3	Strong, durable, little to moderate elasticity, resistant to moisture/frost	Internal and external structures, foundations
Sulphur concretes	Sulphur 1; Sand/Aggregate 3	Waterproof but still sensitive to frost	Internal and external structures, foundations

Table 13.3 *Lightweight concretes, their properties and areas of use*

Type	*Materials*	*Properties*	*Areas of use*
Aerated concretes	Cement, sand, lime, gypsum, aluminium powder	Moderate thermal insulation, low resistance to moisture/frost	Internal and external construction
Concretes with light aggregate	Cement, expanded clay or similar lightweight aggregate, sand	Low thermal insulation, resistant to frost	Internal and external construction, foundations
Pumice concretes	Cement, pumice, sand	Moderate thermal insulation	Internal and external construction
Concretes with wood chip	Cement, impregnated wood chip	Low thermal insulation, low resistance to moisture/ frost	Internal construction
Woodwool cements	Cement, impregnated woodwool	Moderate thermal insulation	Light internal and external construction

This disturbs the shore and can be damaging to marine ecological systems.

Some concrete aggregates may contain a substantial amount of crystalline silica, which when the concrete is cut or broken can expose the worker, and people in the vicinity, to potentially toxic dust. Aggregates may also contain varying amounts of radioactive material. The levels are low and usually have no effect on the indoor climate. Exceptions to the rule are some slates and industrial aggregates, which can affect the level of radioactivity quite strongly.

In foundations and buildings made largely of concrete, the aggregates will by weight be the single largest component. To reduce transport associated energy use and pollution it is always important to use local sources. Prefabricated concrete elements may involve long distance transport compared to preparing concrete in situ.

HIGH STRENGTH CONCRETE

The production of high strength concrete relies on three main effects (Gielen, 1997):

1. A reduced water/cement ratio always increases the strength. This is done by reducing the tension of the water by adding small amounts of waterglass, natron and/or soda, see page 68.
2. With smaller size particles used as aggregates, the total bonding surface with the cement is larger and less porous.
3. The use of additional fly-ash, silica dust or other pozzolanas can increase the bonding strength.

When the strength of concrete is improved, the weight of concrete building elements can be reduced. A well-mixed high strength concrete can, for example, reduce the amount of concrete needed for columns with axial loads by 30%. For floor elements the effective span can be increased by 40% (Kram *et al.*, 2001).

Reinforcement

Steel is the material almost universally used to reinforce concrete. The steel content ranges from 40 kg per m^3 up to 200 kg per m^3 of

Table 14.4 *Moisture buffer value (MBV) of different materials used on indoor surfaces.*

Material/product	*$MBV_{practical}$ (g/(m^2 %RH))*	*D_p 1% RH for 24 h (mm)*
Concrete	0.35–0.42	6
Cellular concrete (aerated)	0.96–1.11	52
Gypsum	0.57–0.69	33
Brick (well fired)	0.39–0.69	104
Spruce boards	1.15–1.22	16
Birch panels	0.91–1.03	14

D_p decribes the actual penetration depth per 1% change in relative humidity (RH) during 24 hours. All materials are untreated.
(Source: Rode, 2005)

The moisture regulating ability of a material is defined by its moisture buffer value (MBV) (Table 14.4). The moisture buffer value indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity in the surrounding air. When the moisture exchange during the period is reported per open surface area and per % RH variation, the result is the $MBV_{practical}$. The unit for the $MBV_{practical}$ is kg/(m^2 %RH) (Rode *et al.*, 2005). One must remember that most surface coverings and treatment materials such as paints can block the MBV drastically and should be avoided (see Chapter 18).

HYGROSCOPIC SURFACES AND INDOOR CLIMATE

Indoor humidity has a significant effect on occupant comfort. Hygroscopic materials form a cushion for dampness in the same way that a heavy material is a cushion for temperature. This has been shown to provide significant improvement in perceived air quality. During longer periods – particularly in spring and harvest – as many as 25% more people will be satisfied in a bedroom with hygroscopic materials (Simonson, 2002). A moderate and stable moisture situation will also reduce the chances of mites and micro-organisms growing. The deposition and emission cycles of dust on inside surfaces will be reduced. Water vapour carries various gas contaminants combined with water vapour molecules (Simonson, 2000). Therefore, hygroscopic walls will even have a moderate air cleaning effect for nitrogen oxides and formaldehyde. This is only effective as long as the gases stay in the material or are broken down inside it.

BREATHING WALLS

In more and more conventional buildings, the indoor environment is provided with fresh air and pollutants are extracted with mechanical ventilation systems. By using hygroscopic materials, the amount of ventilation required can be reduced considerably. The principle for a 'breathing' building is that one uses no mechanical ventilation system at all; all diffusion of gases takes place through the materials. In a house with hygroscopic materials and a vapour retarder – instead of a vapour barrier – it has been concrete. Much of it is recycled from scrap metal, but it is normal to add at least 10% new steel to improve the strength. Steel reinforcement is in the form of bars of varying dimensions, or fibres of approximately 15 millimetres. The use of fibres can reduce the steel needed to half in concrete floors (Gielen, 1997). The distance between expansion joints can also be increased considerably, therefore reducing the use of plastic joint mastics. Other fibres have been introduced more recently in the form of glass and carbon. With carbon it is also possible to produce a reinforcing wire with far better strength properties than steel bars, reducing the climate impact in production by approximately 60% (Gielen, 1997).

In smaller projects it is also possible to use fibres from plant material, normally in a proportion of 2% in volume. Species with long, strong fibres are well suited. One good candidate is thus hemp fibre. Timber fibres are also used and there have also been experiments with bamboo reinforcement in both the former Soviet Union and France in recent years with good results. *Sinarunddinarianitida* is a tolerant species of bamboo that can be cultivated in Europe. *Thamnecolomus murielae* is also a possibility.

Additives

It is quite normal to put a whole range of additives into cement and concrete mixes (see Table 6.10 in Chapter 6). Additives are often organic and more or less volatile, and many of them can cause problems in the indoor climate. Evaporation of irritating substances from residues of oily fluids used on moulds and temporary lathing during concrete casting is a problem in many concrete buildings.

Handling and demolishing concrete can cause a problem with dust including from colouring pigments which can contain heavy metals such as chrome, lead and cobalt. It is possible that the waste process allows seepage into the environment of added tensides, aromatic hydrocarbons, amines, borates, etc. Melamine-based plasticizers can develop poisonous gases during a fire.

SPECIAL CONCRETES

Sulphur concrete is a possible alternative in prefabricated blocks and elements. It is cast by mixing melted sulphur (120–150 °C) with sand and pouring it quickly into a mould for cooling. This is a very simple process and the use of energy is low. Sulphur blocks are even waterproof as long as there are not many fibres in the mix. Sulphur concrete is visually attractive and virtually maintenance-free, without the ‘ageing lines’ that occur with Portland concrete. The development of a sufficiently sound sulphur concrete has not yet been achieved. For some reason the interest in this material disappeared after a very prolific period of use near the end of the nineteenth century, and the idea was first taken up again about 20 years ago by the Minimum Housing Group at McGill University in Canada, which has built a number of houses in sulphur concrete. Since then, experiments have been carried out in Germany and several other countries.

One of the weaknesses of sulphur concrete is that it does not tolerate frequent freezing and thawing – small cracks appear in the block and it will quickly start to decay. This can be remedied by adding materials such as talcum, clay, graphite and pyrites, in proportions up to 20% by volume. Another problem to consider is fire risk, but it has proved difficult to set fire to a sand-mixed sulphur concrete.

Lime sandstone is produced from a mixture of slaked and unslaked lime (5–8%), mixed with 92–95% quartz sand. The quartz sand is excavated from beaches or sandstone with a high quartz content. The stone is crushed to a grain size between 0.1 and 0.8 mm and mixed with pulverized lime. Water is added and the mixture is cast into blocks that harden for 10 hours in a kiln at 200 to 300 °C. Lime sandstone is used structurally like brick, but is also used as stone lining. It cannot be recycled as new aggregate, but can be used as a stable mass.

13.2.2 The durability of concrete products

There are many examples of pure lime mortar keeping its functional properties for 2000 to 3000 years, but there are also examples of Portland cement mortars that have crumbled within 10 years (Grunau, 1980). Some concrete buildings with Portland cement have stood undamaged for over 100 years.

Durability is clearly dependent on the quality of both workmanship and raw materials, as well as the proportions of the mix and the environment of the building. In recent years it has become evident that certain types of air pollution accelerates the decomposition of concrete. Carbon dioxide and sulphur dioxide, both of which occur in high concentrations around industrial areas and towns, are particularly damaging.

It has been proved that carbon dioxide can carbonize up to 40 mm into concrete. This means that part of the carbon dioxide originally released in the production of the cements is reabsorbed (carbonatation). But at the same time, concrete loses its alkaline properties as a result and reinforcements of steel can be subject to corrosion. The next phase of breakdown usually occurs quite quickly, and involves the slow loss of the concrete itself. A wide survey of the Finnish building stock revealed a series of cases where concrete buildings had to undergo extensive repairs within less than 10 years of their completion as a result of carbonatation and insufficient frost resistance (Lahdensivu *et al.*, 2007). In the USA, one bridge per day is demolished as a result of such processes.

Much of today's concrete contains organic additives, and these types of concrete break down even more quickly. Mortars with organic resins have been seen to decay within two to four years (Grunau, 1980).

Geopolymeric cement has good resistance to aggressive urban air, and the majority of Portland pozzolana concrete mixes have a greater resistance to pollution than pure Portland concrete. There is no long-term experience of how lime sandstone and sulphur concrete last. The same can be said for lime concrete, which is seldom used in northern countries.

Concrete can be protected through construction detailing. The most important rule of thumb is to avoid details that are continually exposed to rain. This includes exposed horizontal surfaces, where soot and other polluting particles will settle as well, later to be washed down over the adjacent façades.

13.2.3 Recycling

The value of in situ concrete in terms of recycling is low. It can, however, be crushed and ground to aggregate. The majority has to be sorted and used as landfill. In theory, steel can also be recycled from reinforcement, though this is a complex process using machines for crushing the concrete, electromagnets for separating, etc. Until 1950, smooth circular steel bars were used which were much easier to remove from concrete. Fibre reinforcement has no recycling potential.

Constructions consisting of prefabricated components such as blocks and slabs have considerably better recycling possibilities. By using mechanical fixings or mortar joints that make easy dismantling possible, the whole component can be re-used.

The mortar used for construction with concrete blocks is usually produced with strong Portland cement. The construction is, therefore, very difficult to disassemble without destroying the blocks. Alternatives are the different lime mortars, mainly based on hydraulic lime. In some cases, weaker mortar may require compensation in terms of reinforcement. The end connections of larger concrete units like slabs, beams and columns are usually grouted. Floor slabs are often covered with a concrete topping or a cement screed. These constructions should be avoided and substituted with bolted connections, which make dismantling a lot easier without the risk of damaging the elements (Figure 13.7). Beams, columns and slabs reinforced with bars or wires cannot usually be cut and refitted in the same way as steel structures, and should therefore initially be produced in standardized dimensions. It is imperative that all steel reinforcement is well-covered by the concrete, to prevent corrosion. When recycling older concrete elements, one must analyse the material since it may contain asbestos fibres or even PCB which at one stage was used as additive in many concrete mixtures.

13.7

Norwegian re-usable foundation system in concrete units. All the components are standardized and locked together internally with grooves and bolts. During demolition, the ties and pillars are lifted up, leaving only the bases of the pillars standing in the ground. The rest is quality-controlled on site and then transported directly to a new building site. Gaia Lista, 1996.

In Denmark and Sweden there are many examples of industrial and agricultural buildings almost entirely built of recycled concrete units. In former East Germany, prefabricated elements from large apartment blocks have been shown to be re-usable (Asam, 2007). For many years, the Netherlands government has subsidized development of re-usable concrete constructions and this has led to a number of new structural solutions.

Sulphur concrete can be melted back to its original state, and aggregate can be removed by sieving and possibly be re-used.

13.3 STONE STRUCTURES

Basic info is found in Chapter 7.

The earliest remains of stone buildings in Northern Europe are of longhouses with low walls of stones taken from beaches and fields. They were probably jointed with clay. Walls of stone with lime mortar began to appear around 1000 AD, with stone from local quarries. The stone buildings of this period were almost without exception castles and churches. It was not until the twelfth and thirteenth centuries that quarry stone was used for dwellings, and then mainly for foundations

13.8

The remains of a bronze age dry-walled structure in Ireland.
Source: Dag Roalkvam.

and cellars. Foundation walls of granite were used until the 1920s, later in some places. During the Second World War in Ireland stone became more widely used, but this was relatively short-term.

Extraction and production of stone blocks has a low impact on nature and natural processes. Low technology machinery, well suited for decentralization, is sufficient. Energy consumption is low, as is pollution. Within buildings some types of stone can emit radon gas, though the quantity is seldom dangerous. The recycling potential is high, especially for well-cut stones that have been used in a dry stone wall.

Irregular stones found loose in the ground field stones are easy to get hold of but are limited in their use. More mortar is needed with undressed stone and it thus loses some of its ecological advantages. Due to its weight all the positive aspects of stone construction disappear if the stone material has to be transported long distances. Stone must be a local building material.

13.9

Traditional English dwelling constructed in natural stone.

13.3.1 Structural elements

Natural stone for use in structural stonework should have no trace of decay, splitting of layers or veins of clay. Sandstone and limestone can only be used above ground level; other types of stone can be used both above and below ground level.

Field stones or stones from quarries can be used. Quarry stone can be divided into the following categories:

- *Normal quarry stone* has been lightly worked.
- *Squared stone* is produced in rectangular form and has rough surfaces.
- *Dressed stone* is also rectangular, but the surfaces are smoothly cut.

13.10

Protective dry-stone wall at the Norwegian coast.

The last two types are often called rough and fine-squared stone. If the dimensions of the stone are greater than 20 × 20 × 40 cm, it becomes too heavy to be lifted manually and must be placed by crane. Stone should dry for some time before being used.

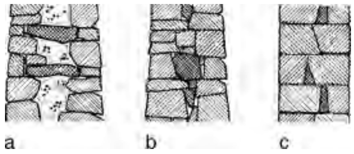
Cutting granite, gneiss, sandstone and most slates releases quartz dust, which can cause serious lung damage.

Masonry

When building with stone particular care needs to be taken at the wall corners. Normally larger squared stones are placed here, whilst the rest of the wall can consist of smaller lightly worked quarry stones or rubble.

Dry-stone walling demands great accuracy and contact between the stones; it is a real craft (Figures 13.11 and 13.12). The stones have to be placed tightly against each other vertically and through the depth of the wall. Small flat angular stones are put into the joints to fix the stones. Here fully one quarter of the area should have bonders in the form of stones that go through the whole thickness of the wall between the inner and outer leaf.

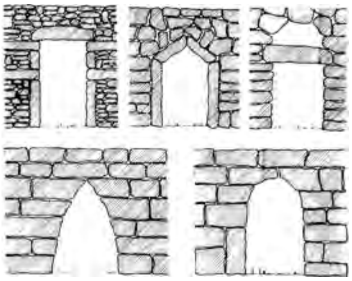
Dry-stone walling is particularly appropriate for foundation walls as it will prevent any capillary action from occurring – no water can move upwards in such a construction. This form of wall is not windproof. One solution is to have two leaves or parallel walls, with earth or other appropriate fill between them.



13.11

Dry-stone walling techniques. (a) Cavity wall in field stones is filled with small stones in mortar, clay, lightweight clay aggregate or fossil meal. On the outer leaf the stones should slope outwards so that water runs off. The top of the wall can be protected with slates or a hydraulic mortar. The wall has moderate insulating and moderate to good wind proofing properties as a sheltering wall. (b) Solid wall in field stones can be rendered for stability whilst (c) Solid wall in cut stone is very stable. Both walls (b-c) require additional insulation as house wall. They are best used in foundation walls or foundations to plinths.

Walls bonded with mortar. Many different mortars can be used for masonry (see Table 17.1 in Chapter 17). Generally, lime mortar and cement-lime mortar are the most suitable. The important properties are elasticity and low resistance to moisture penetration, because the



13.12

Openings in stone walls.

stone itself is resistant to moisture penetration. This is especially important for igneous and metamorphic rock species, which can cause condensation problems on the external walls of a normal warm room, no matter which mortar is used. With the exception of marble, sedimentary rocks are best suited for this purpose.

For heated buildings stone is best used for foundations. The exceptions are limestone and sandstone that can well be used for wall construction in milder climates. Both are, however, sensitive to aggressive atmospheres, in the same way as concrete. They are also susceptible to frequent freeze-thaw cycles. These as well as increased precipitation are expected to increase in regions such as Northern Europe and Russia as a result of global climate changes. In other parts of Europe these risks are likely to decrease.

13.4 STRUCTURAL BRICKWORK

Basic info is found in Chapter 8.

Brick structures have been used in many cultures for thousands of years. In Europe it was not until the middle of the twentieth century that brick was widely replaced by concrete as a main structural material, and since then it has often been used to clad concrete structures. In addition to being more durable than concrete, brick is easier to repair by replacement with new bricks.

Brick has a low tensile strength, which means that it is best used structurally in columns, walls and vaults of a smaller scale. Its uses can be widened through reinforcement and in combination with steel, concrete or timber. Both spans and the overall size of building units can increase and brick can be used in beams and floor slabs.

In normal brickwork, brick represents approximately 70% of the volume, the rest being the mortar. A wide range of mortars are used, usually based on Portland cement, sometimes mixed with lime. The necessary strength can also be achieved using lime mortars. When lime mortars are used there is usually no need for expansion joints due to the high elasticity in the resulting brickwork. See Chapter 17 for a more thorough presentation of mortars.

Brick is a heavy material that often needs to be transported over long distances with resulting pollution and climate gas emissions. Brick production itself also seriously pollutes the environment and is very energy consuming. But bricks need low maintenance and are very durable – in the majority of cases outlasting the other materials in a building. Dieter Hoffmann-Athelm expresses this fact in his paradoxical critique of civilization: 'Brick is almost too durable to have any chance nowadays'. Bricks can withstand most chemical attacks except for the strongest acids. Drains made of the same material as bricks – fired clay – withstand acidic ground conditions, whereas concrete pipes do not (Table 13.4). It is, therefore, important that the design of brick structures is done so as to facilitate future planning of recycling. This would make brick more competitive and attractive from the environmental point of view.

Large emissions of sulphur dioxide from the brick industry can be relatively simply filtered, or else reduced by adding lime to the clay. The

Table 13.4 *Use of fired bricks*

Types	*Firing temp (°C)*	*Properties*	*Areas of use*
Vitrified bricks	1050–1300	Very hard and frost resistant	External walls, flooring, lining of concrete walls, foundations
Well-fired bricks	800–1050	Hard and frost resistant, slightly absorbent to moisture	External walls, lining of concrete
Medium-fired bricks	500–800	Medium resistance to frost, very absorbent to moisture	Internal walls, inner leaf of cavity walls, rendered external walls, moisture-buffering
Low-fired bricks	350–500	Not frost resistant, highly absorbent to moisture	Internal walls, inner leaf of cavity walls, well-rendered external walls, moisture-buffering
Cellular bricks	Approx. 1000	Moderate thermal insulation, hard and medium frost resistant, slightly absorbent to moisture	Internal walls, inner leaf of cavity walls, rendered external walls
Zytan	Approx. 1200[1]	Good thermal insulation, very hard and frost resistant	Thermal insulation, external walls, lining of concrete

[1] Fired in two rounds.

Table 13.5 *Amount of work hours needed to erect 1 m^2 of earth wall, according to an investigation by the Norwegian Building Research Institute in 1952, (Bjerrum et al., 1952), the gross time also including surface treatment*

Method	*Work hours/m^2 wall, net*	*Work hours/m^2, wall gross*
Pisé by machine	3.5	5.0
Pisé by hand	5.5	7.0
Adobe by machine	3.5	5.0
Adobe by hand	5.5	7.0

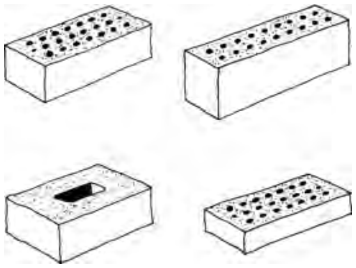
The equivalent for a fully completed concrete wall with surface treatment is 3,3 hours/m^2 whereas a brick wall takes 3 hours/m^2, but those figures only take into account the amount of work carried out on the building site itself. In the case of concrete and brick a large amount of work has been done before the materials actually arrive at the site.

total energy consumption can be greatly reduced by differentiating the use of bricks into well-fired and low-fired products. Today, only well-fired bricks are produced in most countries, even though low-fired alternatives could be used for many purposes. This was common practice until around 1950.

In Northern Europe brickwork, including porous mortars and brick qualities, runs a risk of frost damage during winter if placed in exposed positions. This risk is expected to increase due to climate change in Northern Europe but to decrease farther south, which opens up for wider use of low-fired brick and lime mortars. A well-rendered brick wall can, however, cope with most situations, as demonstrated in many older buildings in parts of Northern Europe exposed to frequent frost through centuries. For more on plasters see Chapter 15.

In the completed building brick is considered a healthy material. Bricks with a high lime content as well as most low and medium-fired bricks also have good moisture regulating properties that help stabilizing indoor humidity. For maintenance, conventional washing brick walls with hydrochloric acid can cause problems in indoor climates.

13.4.1 Brick products

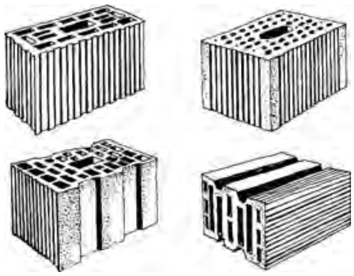


13.13

Examples of perforated bricks.

There are three main types of structural brick: solid bricks, perforated bricks and cellular bricks. The latter two can also be produced in the form of larger block elements. In cellular bricks, various light constituents are added to increase the thermal insulation properties (see Chapter 14). Perforated bricks and blocks are widespread; they use less clay and have a slightly better insulation performance. Bricks with up to 40% perforation can have the same strength as bricks with 20% perforation. They require however additional mortar because of the many holes. Smaller holes will reduce this problem.

The size and form of bricks has varied widely, depending upon the culture and period of use. The Romans usually fired square or triangular bricks 4 cm thick and up to 60 cm in length. They also produced semi-circular and ornamental bricks. The rectangular structural brick has, with very few exceptions, always been formed on the principle of its length being twice its breadth plus the breadth of a mortar joint. The British Standard brick measures 215 × 102.5 × 65 mm. The mortar joint is usually 10 mm.



13.14

Examples of perforated blocks.

On the continent the use of large hollow brick blocks for floor slabs and beams is widespread. In hollow block beams, the structure is held together by steel reinforced concrete, whilst slab units are only partly structural as they are held between beams of either hollow blocks or concrete.

13.4.2 Recycling

In theory, the lifespan of bricks is at least 1000 years (Gielen, 1997); if re-used it can thus serve many generations of buildings. This well justifies its high energy consumption and emissions of carbon dioxide and other effluents during production.

Historically brick has often been recycled, as by the Anglo-Saxons who did not manufacture brick themselves but systematically re-used the distinctive large flat bricks left by the Romans. Similarly with the dissolution of monasteries during the Reformation, many churches and religious buildings were used as 'quarries' for bricks and building stones, which were re-used on a large scale. Around 1935, strong mortars containing a large proportion of Portland cement became common, making it far more difficult to recycle modern walls.

To recycle brick the mortar has to be weaker than the brick, or the brick will easily break. Lime mortars, including where necessary a maximum of 35% Portland cement, make it much easier to dismantle a construction made in brick masonry. The more lime the better. In Japan a new technique of brick masonry without mortar has been developed, with the goal of making recycling easier (Hayashi *et al.*, 2005). Instead of mortar, steel ties are used in quite large quantities. It is uncertain whether the resulting environmental impact is in fact much less, even given several cycles of re-use.

13.15

Small building constructed in recycled brick by students at The Technical University of Lund, Sweden.

There is no technically efficient method for cleaning old bricks; it has to be done by hand and is relatively labour intensive. There are,

13.16

Wall with a mixture of recycled bricks and stones.

however, studies in progress involving the use of pressure waves to break the bond between the mortar and the bricks. This may become a viable solution and lead to more brick recycling opportunities in the near future. Regardless of the method used, old mortar will be chemically bound in the pores of the brick, making it more difficult to bind new mortar. Re-use is therefore most relevant for partition walls and small external walls where the functional requirements are lower. If one side of a brick is covered in soot from an old chimney, this must never face the outside since the soot will attack the wall surface rendering.

Bricks that cannot be dismantled can be crushed and in certain cases used as pozzolana in cement. Larger pieces of brick can be used as aggregate in concrete. In Denmark, blocks are manufactured with pieces of brick used as attractive, visible aggregate.

SMALLER BRICK STRUCTURES

Brick structures above ground can be built as walls, columns, arches and vaults. Arches and vaults are used in roof construction, and arches of brick are the most common way of spanning an opening for windows and doors without having to use steel reinforcement. The following rules of thumb should be used when building a complete wall without reinforcement:

- The building should not be higher than two storeys.
- The largest distance from centre-to-centre of structural walls should not exceed 5.5 m; the distance between bracing partition walls should not be more than 4–5 m.

13.17

Old bricks can be cut into tiles with thickness approx. 1,6 cm and used as flooring. Source: Stavne gård.

- Main loadbearing walls should be at least 20 cm thick, i.e. two bricks wide. Alternatively, they can be one brick thick in lengths of a couple of metres between 30 × 30 cm buttressing columns.
- Window and door openings should as far as possible be above one another.

Both solid and cavity walls can be built. Solid walls are straightforward to build, and can be insulated either inside or outside, e.g. with wood-wool slabs which can be plastered or rendered. If the insulation is on the outside the brick's capacity to store heat is better utilized. Internal insulation means the walls will be cold towards the outside, increasing the risk of frost damage.

Cavity walls are normally two leaves of single brickwork with a distance between them of 50 to 75 mm. A hard fired brick that will withstand frost is necessary in the outer leaf. Extra hard-fired bricks that are highly vitrified have a low capacity for water absorption and should therefore be ventilated behind. If the outside surface is to be rendered, bricks fired at lower temperatures can be used.

The inner leaf can be made of middle or low-fired bricks. Low-fired and porous bricks must be soaked before laying so that they do not absorb much moisture from the mortar. Low-fired brick binds well with clayey binders such as hydraulic lime, but less well with pure lime products (see Table 17.1).

The leaves are usually bonded together with simple steel ties. In cold climates, the cavity is usually filled with insulation, preferably of mineral origin, such as perlite, vermiculite, expanded clay clinker or granulated and expanded waste glass. In areas where there is heavy driving rain, it pays to render the inside of the outer leaf too. Beams resting on the inner leaf should be surrounded with impregnated building paper to avoid humidity damage. Birch bark is also an option.

A vapour-tight render or paint should be avoided on the outside, since it will quickly result in frost damage. Good alternatives are hydraulic lime render and silicate paints.

13.5 EARTH STRUCTURES

Basic info is found in Chapter 8.

Earth structures consist either of rammed earth executed on site between shuttering (*pisé*), or of earth blocks laid in mortar (*adobe*). These two main techniques are suitable for buildings of domestic scale and considerably larger (Figure 13.18). Even with large amounts of plant fibres mixed in, the material is fireproof. Earth is also an excellent regulator of humidity. The oldest complete earth building in Europe, dating from 1270, is in the town of Montbrisson in central France. It now houses a library for moisture-sensitive books.

Earth buildings have many ecological advantages. Earth is a perfect material in terms of resources, pollution and indoor climate, and when the building is no longer needed, it simply reverts back to the earth.

Earth has, however, structural limitations as a building material since its compressive strength is fairly low. This is compensated for by building thicker walls. The increase in the amount of material used does not really matter if the source of earth is near the site.

Earth in itself does not have a particularly high thermal insulation value; better than concrete, and close to brick. However, the versatility and thermal capacity of plain earth constructions is good. By adding organic fibres or expanded clay aggregate the insulation value can be improved. Solid earth walls are best for buildings with low internal temperatures, or with external two-leaf walls containing a cavity. An exception to this is lightweight straw loam, see page 283.

13.18

A six storey earth building erected in Weilburg (Germany) in 1827. Photo: Oliver Abels.

As earth constructions are voluminous and heavy they should be based on local resources. Transport of adobe blocks is also subject to considerable wastage, since the blocks are not particularly strong.

13.5.1 Suitable types of earth

For pisé construction, earth must be dry enough for the shuttering to be lifted directly after ramming without damaging the wall. Shrinkage needs to be as little as possible to avoid cracks. A well-graded earth with about 12% clay is best. An earth mixture with up to 30% clay is usable, but will be harder to form. Sand can be mixed with earth that has too much clay, and clay can be added to earth that has too little.

For adobe blocks a much more fatty earth with up to 40% clay (or even more in blocks mixed with straw) can be used.

13.5.2 Stabilizing aggregate and other additives

In certain situations it may be necessary to add stabilizers. These usually have three functions:

- *To bind the earth particles together strongly*. These are substances such as lime, Portland cement, pozzolana cements and natural fibres. These strengtheners are necessary for buildings more than two storeys high, whatever the quality of the earth.
- *To reduce water penetration*. Lime, Portland cement, pozzolana cement, bitumen and waterglass are examples. Traditionally whey, casein and oxblood have also been used. In areas where there is a great deal of driving rain it is advisable to have one of these additives in the earth mix, and in extreme conditions a separate external cladding as well.
- *To avoid shrinkage*. This is mainly achieved by natural fibres, even though cement and lime can also be used.

Lime and cement. Lime is the stabilizer for earth rich in clay. Both slaked and unslaked lime can be used. The lime reacts with the clay as a binder and can be added in a proportion of 6–14% by weight.

Portland cement is often used as stabilizer for earth rich in sand or containing little clay. The proportion of cement to earth is 4–10% by weight. Mixtures with Portland cement are also used in foundation walls. The humus in the earth can attack the cement, so this construction technique is assumed to have low durability.

Pozzolanic cement can be used in both types of earth, either lacking or containing a lot of clay. It has to be added in slightly larger quantities than with Portland cement.

Adding cements or lime based additives increases the environmental impact and energy use. All lime and cement constituents also reduce the possibility of recycling the earth after demolition or decay.

Natural fibres are best used in earth containing a lot of clay to increase thermal insulation and reduce shrinkage. A mixture of even 4%

by volume of natural fibre will have a very positive effect on shrinkage and strength. Common proportions in the mixture are 10–20% by volume. Larger amounts than this will reduce its strength. In non-structural walls that are primarily for thermal insulation, fibre content is sometimes increased up to 80%, see Chapter 14.

Straw chopped into lengths of about 10 cm, preferably from oats or barley, is normally used. Pine needles are also good binders; alternatively stalks from corn, flax, hemp, dried roots, animal hair, twigs, sawdust, dried leaves and moss can be used.

If large amounts of organic material are used, mould can be a problem. These walls must thus dry out properly and should not be covered until the moisture content has been reduced to around 18%.

Expanded mineral products such as exfoliated vermiculite, expanded clay pellets and perlite can be used as aggregate. There is no chance of mould, and higher thermal insulation is achieved. However, mineral aggregates require much more energy to extract and produce than natural fibres, with large emissions of carbon dioxide as a result.

Waterglass. An earth structure can be made more water resistant by brushing a solution of 5% waterglass on the surface of the wall. This can also be used for dipping earth blocks before mounting them.

13.5.3 Methods of construction

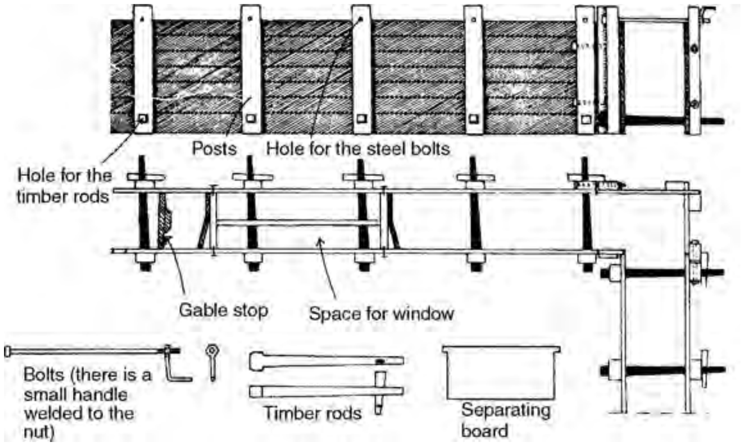
All of the different earth construction techniques demand protection from strong sunshine and from heavy rain. It is also advantageous to build during early summer so that walls are dry enough to be rendered during the autumn.

Foundation materials for earth buildings are stone, earth mixed with Portland cement, lightweight expanded clay blocks or normal concrete. Foundations should be built to at least 40 cm above ground level, so as not to be splashed by rain, and must be at least as wide as the earth wall itself, usually about 40 cm. In concrete foundations the bulk can easily be increased by adding up to 25% of rubble, e.g. fieldstone.

If unprotected, stone and concrete walls can absorb a great deal of moisture from the ground through capillary action – rising damp. In earth buildings this must at all costs be avoided since earth structures are even more sensitive to moisture than timber construction. A damp-proof course must be laid at the base of the wall. This is often done with asphalt, or can be a small layer of strong concrete that also serves as a strengthening ring beam. Slates can also be used.

Pisé (earth ramming technique)

Earth suitable for ramming contains primarily sand, fine gravel and a certain amount of clay which acts as a binder. Ramming consolidates and binds the components. As with all masonry-type materials, walls should be kept humid and should not dry out too quickly. After the



13.19

Swedish model for shuttering.
Source: Lindberg *et al.*, 1950.

building process the wall will be cured by substances in the air and can eventually become almost as hard as chalk or sandstone. Shuttering and further equipment is required for ramming.

Shuttering and ramming equipment. Shuttering must be easy to handle and solid. There are many patents.

MAKING OF A SHUTTERING

Figure 13.19 shows a Swedish model that is easily self-built. It consists of two vertical panels fixed together by long bolts and wooden rods. The panels are made of 30 mm thick planks of spruce or pine. The length of the shuttering should be between 2 and 4 m depending upon the dimensions and form of the building. The panels are 80 cm high and braced by 7 × 12 cm posts screwed to the boarding. The screws are 64 cm apart.

The spacing of the posts depends upon the thickness of the wall, usually 40 cm. On the bottom they are held together by timber rods, whilst the upper parts are held together by steel bolts 18 mm in diameter. The rods are made of hardwood such as beech, ash or maple and are conical. The dimensions at the top of the rod are 6 × 6 cm and at the bottom 4.5 × 4.5 cm. The holes in the posts should be slightly larger so that the rods are loose. The gable ends of the shuttering have a conical post fixed with nails. To prevent the shuttering falling inwards, a couple of separating boards are needed inside the shuttering.

In order to form openings for doors and windows, loose vertical shuttering is placed inside and nailed through the shuttering panels. These can then be easily removed. It is quite possible to mount shuttering after each other as long as they are well fixed.

The ramming can be done either manually or by machine. When ramming by hand, ideally three rammers with different forms are needed (see Figure 13.21). The handle is heavy hardwood and the rammer is made of iron. The weight of a rammer should be around 6–7 kg.

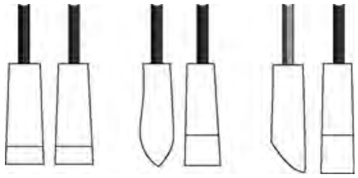
Ramming by machine is much more effective. This can be done using an electric or pneumatic ram with a square head of 12 × 12 cm. A

13.20

Ramming earth with pneumatic equipment.
Source: Claytec.

robotic rammer which can follow the line of the shuttering is being developed in Germany.

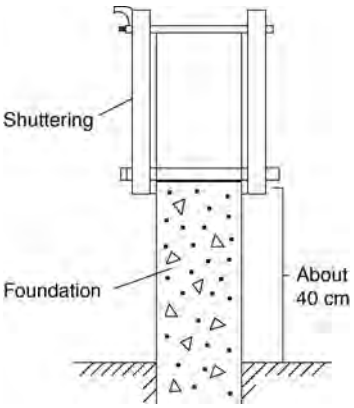
Ramming is best carried out by a working team of two or three people. The wall shuttering is mounted on the foundation walls as in Figure 13.22 with gable ends and separating boards.



13.21

Manual rammers.

When ramming by machine, layers of 13 to 14 cm can be made. This is approximately two-thirds of the volume of the original loose earth. When ramming by hand a layer thickness of not more than 8 cm is advisable. It is important to ram at the edge of the shuttering when machine ramming; starting in the middle may cause stones and lumps to be pushed out to the edge and loosened. The ramming should make the earth as hard as rock – it should 'sing out' – and a pick should not make marks when the surface is hit.



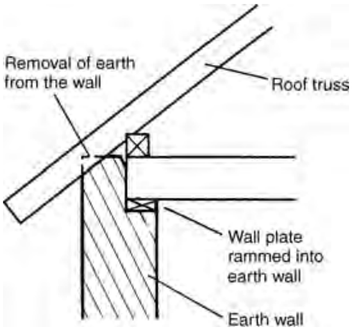
13.22

Putting up shuttering.

When the first layer is ready, the next layer is begun, and so on until the shuttering is full. The rods are then pulled out and the shuttering moved. With each move it is necessary to check that the shuttering is exactly vertical. The conical post on the gable end of the shuttering forms a 'locking key' which is used to increase the stability of the wall.

In the corners, traditionally reinforcement of twigs or barbed wire is used, and after the first layer, holes are cut for the floor beams, which can be placed directly over the damp-proof course on the foundation. As the ramming progresses openings for windows and doors are added, with timber or reinforced concrete beams rammed in over them. Timber does not rot in normal dried earth walls. All timber that is rammed into the walls has to be dipped in water first, and trunks that are rammed into the wall for fixings should be conical, with the thickest end inside the wall, so that it will not loosen. To support the floor joists further up the wall, a timber plate must be rammed in (see Figure 13.23).

When ramming is finished, the holes made by the rods are filled with crushed brick or expanded clay aggregate mixed with a mortar based on lime or loam. After that the roof is put on. A large overhang will protect the wall from rain.



13.23

Ramming in the wall plates to carry structures in roof and floors.

Adobe (earth blocks)

The advantage of building with blocks rather than pisé is that the building period can be shortened. The blocks can be made at any time, providing there is no frost, and can be stored until needed for building. The construction work should be carried out during spring or early summer so that joints can dry out before applying a surface rendering. As already mentioned, there must be a higher percentage of clay in earth for blocks. There should be no particles larger than 15 mm in the mix. Hard lumps of clay can be crushed in special crushers (see Figure 13.24).

A certain amount of coarse plant fibres, such as chopped straw, is usually added to stop cracking due to shrinkage, and just enough water to make the earth more pliable before use.

Moulds. Loose moulds of wood or metal, and even mechanical block moulds, are available. The size of moulds can vary, but 'monolithic' blocks are usually 75 × 320 × 50 cm and mini-blocks are the same size as bricks. Larger blocks for use in partition walls are made in dimensions up to 520 × 250 × 100 cm; these are commercially available in large parts of Europe. Such blocks are often made with significant amounts of wood shavings added, and may be perforated to reduce weight and facilitate drying during production.

Simple wooden moulds can be nailed together quite easily. Mechanical block moulds have capacities that vary from 300 to 3000 blocks per day. These are easy to transport and are used manually or driven by a motor.

13.24

Manual clay crusher.

Pressing the blocks. The earth mix is rammed into the mould, ensuring that the corners are well filled, and excess earth is then scraped off with a board. After a few hours the blocks are ready to be removed from the mould, and after that be stacked so that air can circulate around them. This should take place in the shade and well protected from rain. After two weeks the blocks are dried well enough for building.

Laying earth blocks. The mortar used is usually the same earth that the blocks are made of, mixed with water and even some lime. Mortars based on Portland cement should not be used as they are less elastic and can split the earth during shrinkage. Blocks are laid in normal coursing, often after being dipped in a waterglass solution to saturate them. Barbed wire, chicken wire or plant fibres are recommended in every third course as reinforcement. It is also possible to construct ceiling vaults from earth blocks.

Good protection against moisture and rising damp are critical. In rough climates a good rendering or other cladding is advisable in any case, see page 216.

13.25

Adobe. Gaia Lista, 1991.

Other earth-building techniques

Adobe and pisé are the most widespread of earth-building techniques, but other techniques also have interesting aspects. The most important alternative techniques are cob, earth loaves, earth strand technique and earth filled hoses.

COB WALLS

As with earth blocks, earth used for cob constructions is relatively rich in clay. The earth and cut straw is mixed in a hole in the ground in the proportion of 50 kg straw to 1 m^3 of earth. The more clay the earth contains, the more straw is needed. The ready mixed earth and straw is then thrown into the shuttering of the wall and rammed down by foot. Between adding each course of about 50 cm, the wall is left to dry out for about two days.

When the wall has reached full height, the vertical is checked and excess earth removed with a trowel, so that the wall has an even thickness. A clay mix or gruel is smeared over the whole wall and it stands under cover until it is dry, from three months to a year. Shrinkage is quite considerable, about 1 cm per metre, so it is a mistake to render a wall before it is totally dry. Because of the long intervals in the process, this building technique is seldom used nowadays. Cob used to be the main technique used in the United Kingdom, and there are many old examples still standing which prove that this is an excellent system (Figure 13.26).

EARTH LOAVES

This technique is a very simple earth building method brought to Europe by a missionary who learned it in East Africa. The German school of agriculture at Dünne further developed the method during the 1920s, and since 1949 about 350 buildings have been constructed in Germany using this technique. 'Loaves' are formed by hand from well-mixed earth containing a high percentage of clay (Figure 13.27). These clay loaves measure about 12 × 12 × 25 cm.

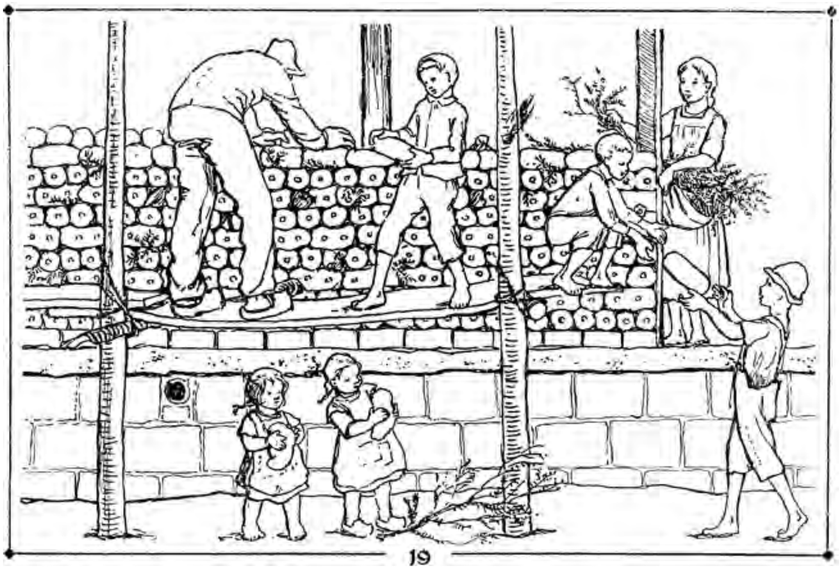
The walls are built by laying the loaves on top of each other as in normal bricklaying, as soon as they have been kneaded, at a rate of four courses each day. They are reinforced with sticks every third course and at every course in the corners. After four to six weeks drying time the wall is strong enough to take the roof. The roof is often put up provisionally beforehand to protect the walls against rain during the drying period. The earth loaf technique can also be used for internal walls, with or without a loadbearing function.

13.26

The manor house of Skinnarbøl in south east Norway from the early 19th century is built in the cob technique.
Source: Rolf Jacobsen.

EXTENDED STRAND TECHNIQUE

This method has been recently developed by the Technical High School in Kassel, Germany, and is a development of the earth loaf technique. In this case there is not as much clay in the mix, as shrinkage would cause a problem, but the amount of clay must be enough to give the mix a certain elasticity.



13.27

The earth loaf technique.
Source: Verein *Heimstätte*, Dünne.

The earth is put in an extruding machine used for bricks (see Figure 8.6), compressed, and then extruded in tubes of 8–16 cm in diameter. The capacity of the machine is 1.5 m of tube per minute, and the length is unlimited. The material is so well compressed from the start that it can be combined and built without waiting for the lower layer to dry out. With a mobile extruding machine a house can be built in a few days in the same way that a vase of clay is made with long clay 'sausages'. Mortar is not necessary, but the walls must be rendered afterwards. This technique is still at an early stage of development.

EARTH FILLED HOSES

Visually this building technique is similar to extruded earth tubes. The earth has to be as free of clay as possible, mostly pure sand which has no binding properties. The 'binder' is jute sacks which are 2.6 m long and about 0.5 wide. The sand-filled sacks are piled up as walls within a light timber framework. The sand can also be mixed with hydraulic lime mortar or cement, and the sacks dipped in water before being piled up, so the mix becomes hard enough to make the slightly temporary binding power of the sacks superfluous. It is also possible to add some lightweight aggregate to increase the insulation value.

Surface treatment

Weather protection of exposed earth structures is important. The outside and inside walls can be rendered with hydraulic lime or lime cement plaster. The inside can also be rendered with lime or clay plasters, (see Chapter 15). Walls exposed to extreme weather should be protected by timber panelling fixed to battens nailed directly onto the earth wall. The nails usually fasten to the earth wall without any problem. Internal walls can also be covered with panelling or wallpaper, or painted with mineral or casein paints. The surface of the walls must not be treated with a vapour-proof paint, as this would quickly lead to moisture gathering inside the wall, thus allowing frost damage.

13.6 TIMBER STRUCTURES

Basic info is found in Chapter 10.

Timber has been the main structural material for the nomad's tent as well as the sedentary farmer's house in all corners of the world, especially for roof construction, where its lightweight and structural properties have made it more attractive than any alternative.

On the basis of relative weight, high quality timber is stronger than steel. The safety factors needed in the design of wood structures are, however, high. The average strength is ten times higher than the design strength. The reason for this over-engineering is the occasional irregularity in the wood that means that it may be weak in a few places. Good selection can reduce this.

Timber structures have usually been limited to small buildings because of the fire risk; although there are many developments in the use of timber in much larger buildings. The reasons for this are the improved possibilities for technical fire protection and the revised view of timber's own properties in relation to fire, which are better than previously thought. In timber of a certain size, the outer layer chars and then effectively stops further burning of the inner core of the timber.

Building in timber entails much lower environmental pollution and energy use than construction systems in steel, concrete or brick. Substituting these materials with timber would considerably reduce the overall environmental impact of the construction sector. To this can be added timber's function as a carbon sink. As timber grows, every kilogram of wood binds between 1.5 and 1.8 kilograms of carbon dioxide from the atmosphere. This will remain 'stored' until the building is burned or decays. It is thus desirable to maximize use of timber especially in the most long-lasting parts of buildings, such as the structural system.

HISTORY

The first mention of buildings constructed completely from timber in European history is Tacitus' writing about German houses in his *Histories* in AD 98, characterizing them as something 'not pleasing to the eye'. These houses had either palisade walls with columns fixed directly into the earth or clay-clad wattle walls. And they had thatched straw roofs. Excavations from a Stone Age village in Schwaben, Germany, showed that houses like these have been built over a period of at least 4000 years.

Remains of log timber buildings from about 1200–800 BC have been found in the village of Buch outside Berlin. Even in China and Japan there are traces of this technique from an early period, but most likely from a completely separate tradition to that of Europe.

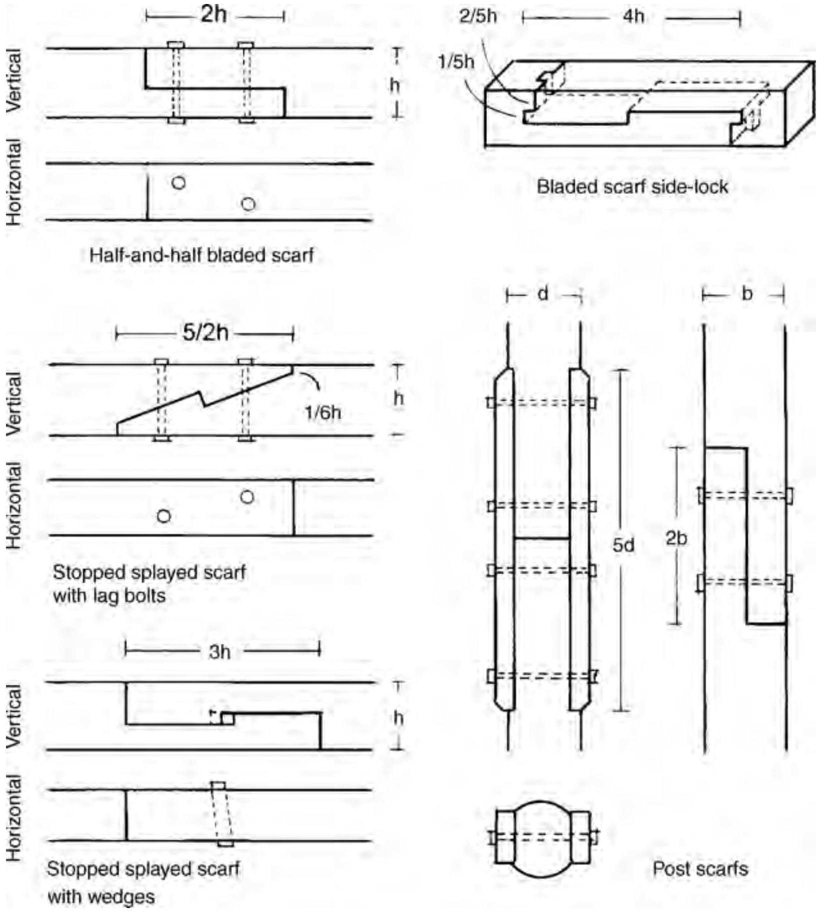
In areas where there is a milder climate, such as the British Isles, the coasts of the continent and Scandinavia, an alternative structural technique developed alongside log construction: the *stave* technique. This technique is best exemplified in all its magnificence by the stave churches, and creates tall airy timber structures from specially grown timber, held together by wooden plugs.

The rendered wattle wall really started to develop when masonry walls were enforced by law. After a series of town fires during the seventeenth century, rendered wattle walls were almost the only alternative to brick and stone.

13.6.1 Structural elements in timber

Materials in solid timber occur in different dimensions, either as round logs or rectangular sections. There is an obvious limitation depending upon the size of the tree that is used, and this varies between different types of tree. Generally, the smaller the size of the component, the more effective the use of the timber available. To resolve the problem of the limitations of some components, timber jointing can be used.

It is necessary to differentiate between timber jointing for increasing the length and for increasing the cross-section. Jointing for increasing the length can be achieved with timber plugs, bolts, nails or glue. It is normal to use spliced joints for sills, logs, columns or similar



13.28

Mechanical timber joints for increasing the length.

components where compressive strength is more important than the tensile strength (Figure 13.28). Certain spliced joints, such as the glued finger joint, have a good tensile strength.

Increasing the cross-section can be achieved by using solid connections or I-beams. Solid connections consist quite simply of the addition

13.29

A roof joint bolted together and stiffened by dowels. No glue is used. Gaia Lista, 1987.

13.30

Toothed beam joint put together of three pieces.

of smaller sized timbers to each other. The fixing elements are bolts, nails or glue. Bolted joints are often complemented by steel or timber dowels to stop any lateral movement between the pieces of timber, as in Figures 13.29 and 13.30. Dowels and toothing were used until the 1920s. Solid laminated timber joints have been in use since the turn of the century, and nowadays usually consist of 15–45 mm-wide spruce planks. Normally there is about 2% glue; common glues used are based on melamin-formaldehyde (MUF and MUPF) or phenol-formaldehyde (PF), but polyurethane adhesives (PU) are also used.

Laminated veneer lumber uses multiple layers of thin wood assembled with adhesives, (see pages 339-340 in Chapter 15). The amounts of glue are somewhat higher here and phenol-formaldehyde adhesive (PF) is commonly used. Oriented strand lumber is manufactured from flakes of wood (see pages 339-340 in Chapter 15). In this case there is 6 to 8% glue, often combinations of glues such as melamin-formaldehyde in the centre and the rest with polyurethane glues.

I-beams consist of an upper and lower flange with a web in between (Figure 13.31). The web can be formed of solid timber, steel, veneer, chipboard or fibreboard. The first two are usually fixed by plugging, bolting, nailing with nails or nail plates, while the others are glued. I-beams are a very economical use of material in relation to their strength, and can be used in roof, floor and wall construction.

The energy consumed in the production of glued products is considerably higher than for plain timber products. However, glued products often need less timber since the glues compensate for weaknesses in the timber to some extent.

Structural elements that are bolted together can be more easily dismantled and recycled. Larger nailed and glued products offer a more difficult recycling. In structures where dismantling and re-assembly are anticipated, high quality timber should be used. One should also consider slightly over-designing the components to prevent long-term warping or deformation.

The synthetic glues most often used in industrial timber products are usually derived from fossil oils, causing pollution during the production phase, and in many cases carry definite health risks (see Chapter 17). Hazardous chemicals are also often used to provide protection against insects and fungus, see Chapter 19.

13.6.2 The use of timber in building

Timber is a many-faceted structural material and can be used in foundations, walls and roof structures.

Foundations

The most important timber construction methods for foundations are raft and pile foundations. Their main areas of use are as bases for foundation walls and to stabilize weaker ground conditions.

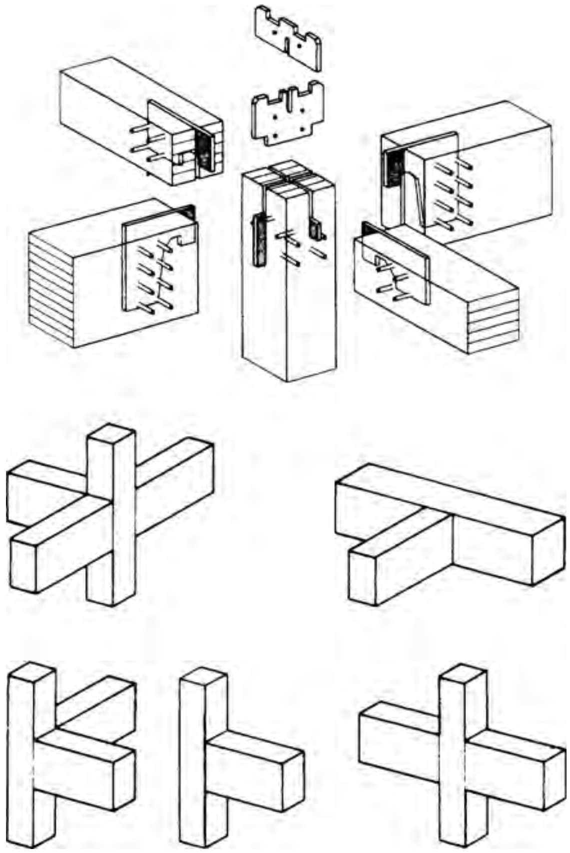
Timbers have varying properties in relation to damp. Some timbers, such as maple and ash, decompose very quickly in both earth and water; spruce is similar. Many types of timber can survive longer in damp and low-oxygen environments rather than in the open air. Pine, alder, elm and oak can last over 500 years in this sort of environment;

13.31

A lattice I-beam in a school building. All joints are fixed by bolting, no glue is used. Gaia Lista, 1998.

larch can survive for 1500 years. As soon as the relative moisture content in timber drops below 30–35%, rot sets in, and durability falls drastically. Certain types of timber are better than others even in these conditions. Oak can survive between 15 and 20 years, whilst larch and pine rich in resin can probably last between 7 and 10 years.

An optimal condition for a permanent timber foundation is an even, rich dampness. The timber should be completely embedded in clay and lie below the groundwater table.



13.32

Demountable timber joints with metal components and plugs.
Source: Janebo.

TIMBER-BASED METHODS OF FOUNDATION WORK

Bulwarking has been used since the Middle Ages, especially when building along the edge of beaches and cutwaters. It is basically a structure of logs laid to form a rectangle, jointed at the corners, measuring 2 to 3 m on each side and filled with stones to stabilize it (Figure 13.37). A bulwark has an elasticity in its construction that allows it to move, and it can therefore cope with waves better than stone or concrete. If robust timber is used, a bulwark can keep its functional properties for hundreds of years.

Raft and pile foundations. Many large coastal towns are built on raft or pile foundations. If the foundations are continually damp then durability is high. Excavations have uncovered pile foundations of alder and aspen from the Middle Ages that are still in perfect condition, with even the bark of the tree preserved (Lidèn, 1974; Minke, 2006; Rybczynski et al., 1974). Through the increase of tunnelling and drainage systems in many towns, the level of the ground water has been lowered, and because of this, fungus attack on the foundations occur, causing a settling of the buildings.

The simplest form of raft foundation is a layer of logs laid directly onto the ground tied to logs laid across them (Figure 13.38). Masonry columns or perimeter walls are built

13.33

Wood construction in the PLEA Center, Kushiro, Japan 1997.

13.34

A structure designed for re-use. The structure is produced of prefabricated and standardized monomaterial components in wood and concrete, which can easily be dismantled and re-used. Gaia Lista, 1995.

on this foundation, and around the edges layers of clay are packed in. Raft foundations were in common use around the seventeenth century and quite normal up to about 1910, when they were slowly replaced by reinforced concrete foundations.

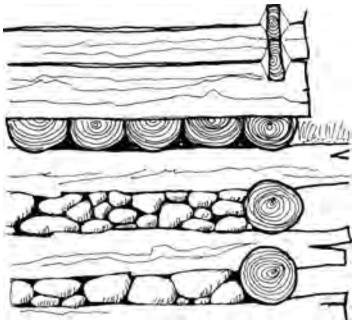
In pile foundations the raft is replaced by vertical logs, which are rammed down into the ground. It is usual to lay three or four horizontal logs onto the piles to distribute the weight evenly, before building the walls. The weight of the building and the bearing

13.35

Playroom at Westborough Primary School, Southend (UK), constructed largely from cardboard made from recycled paper. The cardboard can be recycled again once the products have served their useful life. Architects: Cottrell & Vermeulen Architecture 2001.

13.36

Interior of the cardboard school at Southend.



13.37

Bulwark method of foundation work.
Source: Drange et al., 1980.

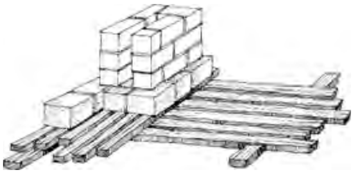
capacity of the earth decide how close the piles need to be to each other. Foundations for smaller buildings usually have thinner piles, from the thickness of an arm down to the thickness of a finger. To distribute the load, a filled bed of round stones may be used. In sandy earth without humus the piles can extend up into the open air. This can provide a simplified solution in certain cases, but even with good impregnation and high-quality timber it is doubtful that such foundations will last longer than perhaps 75 years.

Structural walls

By timber buildings we usually mean buildings with loadbearing timber walls. It is necessary to differentiate between light and heavy structures.

The most important lightweight construction is the framework, which is economical in the use of materials and takes advantage of both the tensile and compressive strengths of timber.

The log building technique is the traditional technique of heavy structures. This method uses a lot of timber and is statically based on the compressive strength of timber. The recently invented massive wood technique exploits both the tensile and the compressive strength. It is therefore also used for loadbearing floors and roof structures.



13.38

Raft foundation.
Source: Bugge 1918.

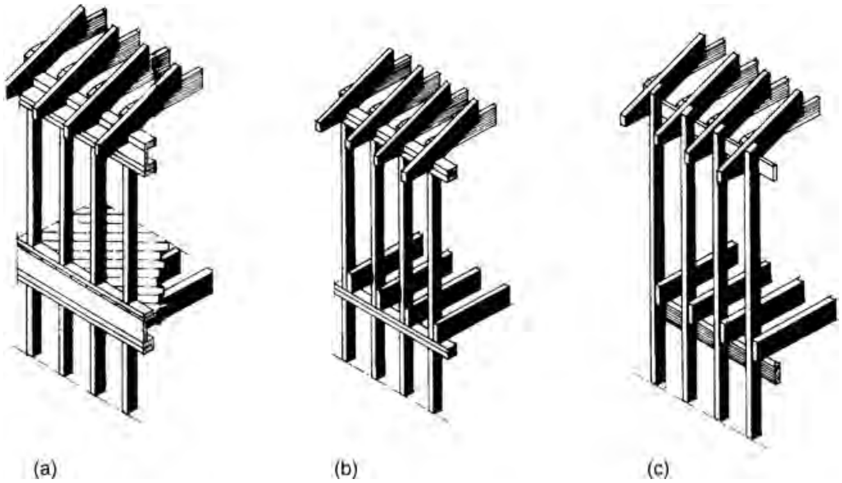
TYPES OF STRUCTURAL WALLS

Structural framework consists of studs mounted between a top plate and a bottom plate, with diagonal bracing added. There have been many variations on this theme through time. Early versions are known as timber framing and use a few large wooden members in the range of 15 to 30 cm thick joined using mortice and tenon or more

13.39

Timber frame construction.
Source: Rolf Jacobsen, Gaia Tjøme.

complex joints that are usually fastened using only wood pegs (Figure 13.39). Later the tendency has been toward smaller dimensions of timber components and more industrialized production (Figure 13.40). This has reduced the quantities of wood needed, but also the quality and strength of the structure to a certain extent. In modern framework the distance between the studs can vary somewhat, from 300 mm to 1.2 m. Until recently bracing was done with diagonal lengths of timber or metal strips, but nowadays it is more usually braced with sheets of fibreboard, plasterboard or chipboard. The spaces between the studs are then filled with different types of insulation. In earlier



13.40

Conventional timber framework. (a) platform construction; (b) balloon construction; (c) balloon construction without sills to allow easy refilling of loose fill insulation from the attic.

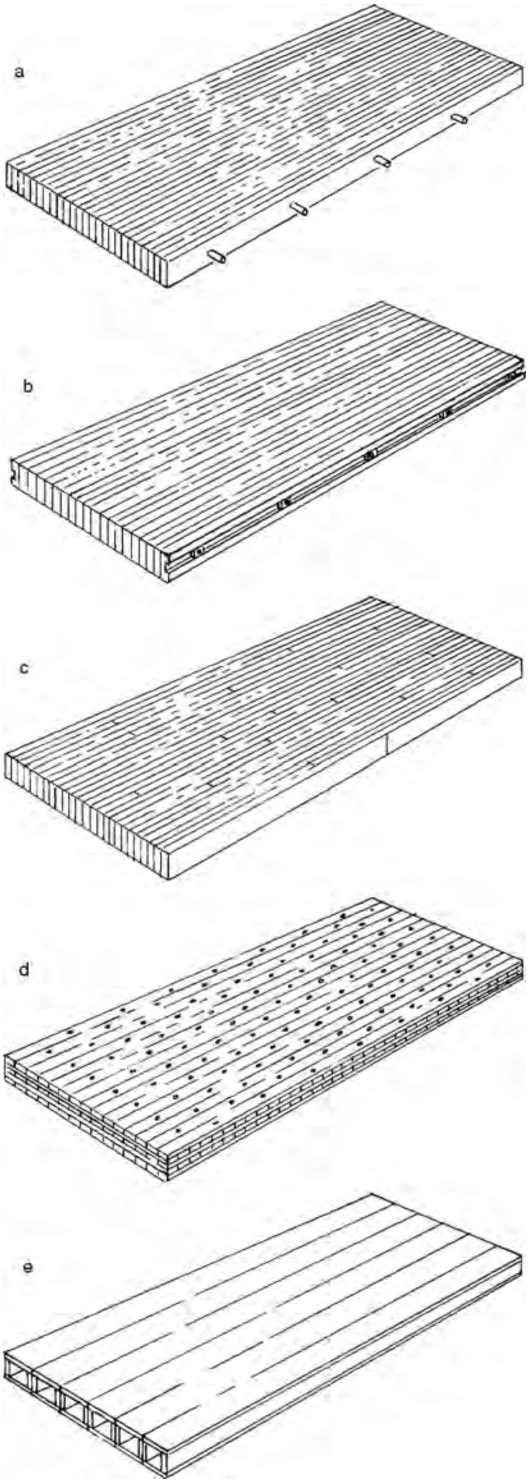
13.41

'The little grey house'. Swedish prefabricated house in log construction. Architects: Sandell and Landström.
Source: Bertil Harstöm and George van der Weyden.

times they were filled with clay (in wattle walls), firewood, or bricks (known as half-timbered brick construction).

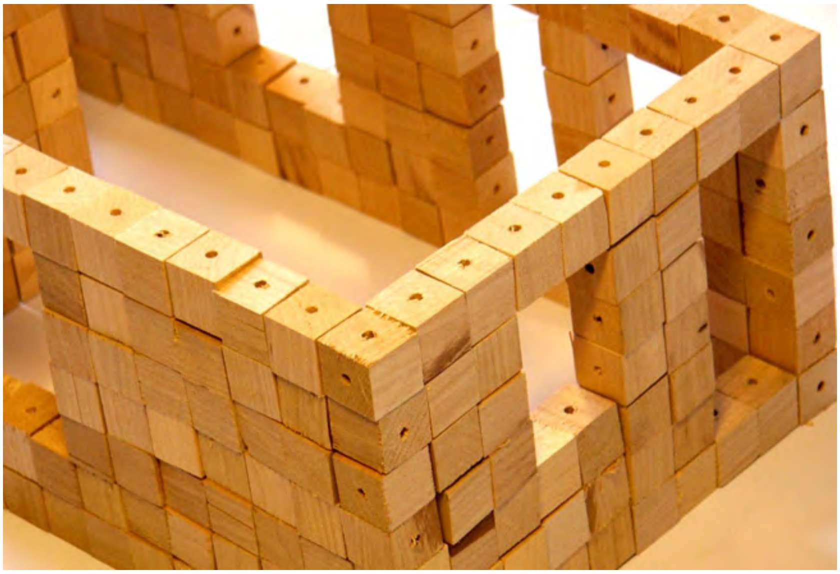
Modern methods of structural framework use timber very economically, but it is seldom easy to recycle. The many and very strong fixings used make the demolished structure suitable only for recycling as pulped raw material for production of wood based boards or burning for energy recovery. Traditional timber framing is more flexible, and easy to dismount and move, or modify.

The timber used in frame construction has to have high strength. It should not be too elastic or deform too much when exposed to moisture. The timbers best suited for this



13.42

Floor elements of massive wood. (a) With horizontal wood dowels; (b) Prestressed with drilled-in rods; (c) Glued; (d) With vertical wood dowels. (e) Glued box elements that can be filled with insulation.



13.43

The 'climate cube' building system consists of massive wooden blocks, see Figure 13.44, piled up to complete walls. The cubes are connected to each other with wooden plugs. No glues are used and the blocks can be easily disassembled for re-use. Gaia Lista, 2005.

are fir, spruce, larch and oak. For smaller structures, birch, aspen, ash and lime can be used.

Timber frame construction is the dominant structural system in the timber building industry today.

Log construction. In this method, logs are stacked directly over each other and notched together in the corners. These buildings are usually rectangular, but can have up to 10 sides.

A solid timber wall has good acoustic properties and fire resistance. The thermal insulation is also good. For 700 to 800 years it has been considered the warmest alternative. However, a log wall needs extra thermal insulation by today's low energy standards. This should be placed on the outside, so as to keep the thermal mass and humidity regulating qualities of the logs in the interior.

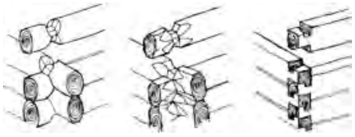
Pine has been the timber most used in log construction. It has often been left open and exposed to the weather, so it has been well tested for hardiness. In log construction with external panelling, spruce can be used. For outhouses birch, aspen and lime can be used. In particularly damp areas, exceptionally durable timber such as oak must be used for the bottom log or sill plate.

There are many ways of shaping the logs and their joints, depending upon which timber is used (see Figure 13.45). Some of these joints are complex and require a high level of skill. Pine should have its surface worked by profiling, while spruce needs only the removal of the bark to keep its strength. Accessible technology and rationality have played a crucial role in the development of techniques. The type shown on the right in Figure 13.45 belongs to the nineteenth-century style of building and was well-suited to the new machinery of the period – sawmills. The disadvantage was that it was difficult to make airtight, and the knots were less strong.

The massive wood *technique* is a fairly recent development. The basic idea is to use fairly worthless low quality planks. These planks are stacked and assembled together into elements. They can be fixed together by glue, nails or with wooden dowels. Large

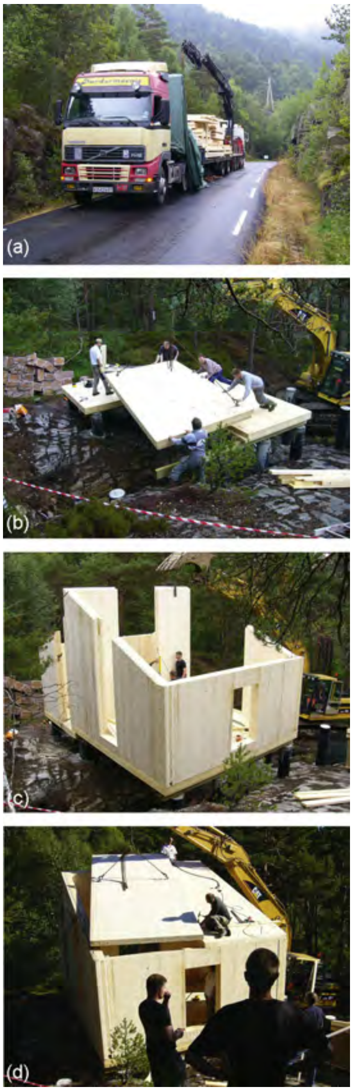
13.44

A climate cube consists of recycled timber panelling and residues from sawmills, rippled and fixed together with wooden dowels. All sides measures 37,5 cm and the thermal insulation value is substantial because of all the closed air gaps formed between the layers. Gaia Lista, 2005.



13.45

Common log joints.



13.46

(A), (B), (C), (D). 4 phases in the erection of a kindergarten in massive wood elements. Rauli, Flekkefjord (Norway). Gaia Lista, 2005.

13.47

Apartment block in massive wood at Svartlamoen, Trondheim (Norway). Architects: Brendeland and Kristoffersen, 2005.

elements can be prefabricated, forming entire sections of walls, floors and roofs. Advanced prefabrication at the factories includes openings for windows, conduits for electric cables and often also the cladding. These elements are then delivered to the site and the whole structure of a building can be mounted with a small crane within just a few days.

Within the massive timber technique quite a number of variations are developing (Figure 13.42). The elements may be from 8 cm to 40 cm thick. Laid as loadbearing floors they can easily span more than 10 metres. Rough or fine surface quality can be ordered. Interior surfaces can therefore be left exposed. An acoustic profile can be given to the underside of a ceiling. In the thickest varieties, plugged together without glue, there are small air spaces between the planks that increase the insulation

13.48

Reggio Emilia kindergarten established in a former motor car repair shop in Trondheim (Norway). Massive woods elements are used as partition walls. Architects: Brendeland and Kristoffersen, 2007.

value so that the wooden element itself needs no further thermal insulation even in cold climates.

Massive timber construction requires fairly low quality wood. Even recycled wood can be used in some of the products (see Figure 13.44). The glued types use synthetic glues, mostly based on melamin, phenol and polyurethane. The amounts used are of the order of 2 to 4% of the total volume of the element. In some types made up with smaller wood flakes, this may be nearer to 6%. Many of these glues have negative environmental effects, as well as possible health effects. Since the surfaces are often left exposed, emissions to the indoor air are a risk (see Chapter 17). Continuous layers of glue may also reduce the humidity regulating performance of the elements.

Glued products will also pose a problem after the building's lifetime and some of these products may have to be treated as special waste. Elements without glue can easily be re-used, especially if they are made in standardized dimensions.

Massive timber elements can be produced in quite small local sawmills using local timber. If the trend moves towards large centralized units, however, the transport consequences will cancel out some of the environmental advantages.

Massive timber construction is, together with log construction, the best method available for increasing the use of timber in construction in order for it to become an important carbon sink for mitigating greenhouse gas emissions.

Stovewood constructions originate in the nineteenth century and represent a building tradition of recycling, where bits of plank and spill from the sawmills are built up into walls using a mortar of pure clay mixed with water and sawdust or chaff (Figure 13.49). A similar tradition is based on cordwood, sometimes set in lime mortar.

The thermal insulating properties of these walls is moderate because of the many cold bridges due to the mortar joints and because wood insulates less in the direction

13.49

Stovewood construction in Latvia.

Source: Rolf Jacobsen.

of the fibres. Stovewood constructions need a couple of years to settle before panelling or wallpapering is done.

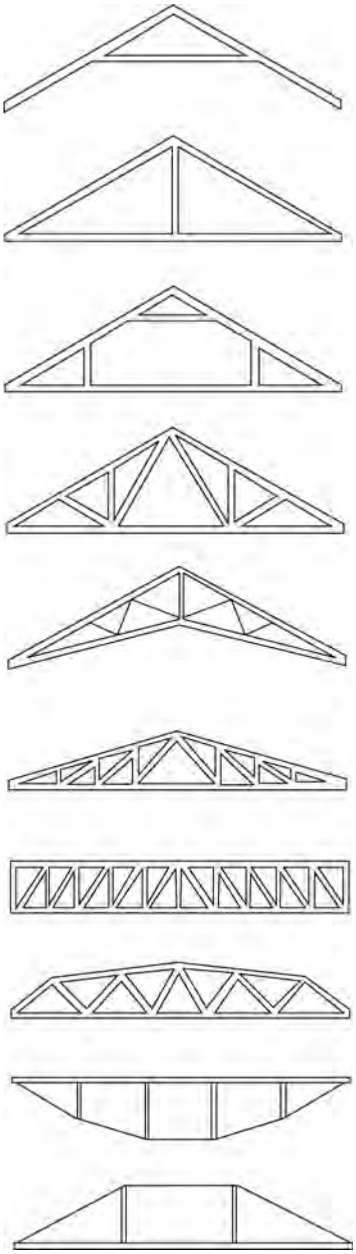
Floor structures

Floor structures in timber usually consist of solid timber joists, composite beams, laminated timber beams or a combination of these. As mentioned above, recent techniques with massive timber elements can provide large spans. For floors between apartments, extra sound and fire protection layers normally have to be added, although the massive timber itself has quite good fire characteristics.

Roof structures

The use of wooden components in roof structures is almost the same as for floors, with beams and massive wood elements as the main options. Many structural alternatives are available through combining them in different ways, including the use of tensile elements such as steel cables (Figure 13.50).

Roofs fall into three main categories: single raftered, purlin and forms made of trusses, with a smaller group known as shell structures.



13.50

Roof trusses constructed in solid timber, some with additional steel wire.

SHELL STRUCTURES

Shell structures are seldom applied despite the fact that they use materials very economically. The timber used must have good strength. It is also an advantage if the timber is light and elastic. Fir, spruce, larch, oak, ash, elm and hazel are best suited.

Shell roofs made of timber have existed for thousands of years, particularly in tent structures. There are two main types: double curved shells and geodesic domes.

Double curved shells (*hyperbolic paraboloid*). A compact version of the double curved shell started to appear in Europe at the beginning of the 1950s in buildings such as schools and industrial premises. Its span varies from 5–100 m. The shell is built in situ over a light scaffolding, and consists of two to three layers of crossed tongued and grooved boarding. The thickness of the boarding is approximately 15 mm. The shells are characterized by the fact that two straight lines can go through any point on the surface of the roof. The boarding is not straight, but the curving is so small that it can bend without difficulty. The shells are put together as shown in Figure 13.51, depending upon the position of the columns.

A lighter version, well suited for small permanent buildings, consists of a rectangular grid of battens. The battens are fastened together at all the intersections with small bolts. The shell can thus easily be put together for transport. When erecting the structure permanently, the grid is fixed to a solid timber frame and the bolts are tightened. This structure can be used for small pavilions or bus shelters, for example.

Geodesic domes. The first geodesic dome was erected using steel in Jena, Germany, in 1922. They have often been constructed in metal or plastics, but timber is also used. The method consists of a simple prefabricated system based on triangles, always assembled into the shape of a hemisphere or sphere. In this way a minimal, stable structure is produced that tolerates heavy loading. The spaces between the grid can be filled with thermal insulation. These domes are used as dwellings in the northern parts of Canada and have been built in many countries. The most common use of them in Europe is for radar stations, though there are reports that their waterproofing is questionable.

13.51

Possible combinations of double curved shells.

Source: Schjödt, 1959.

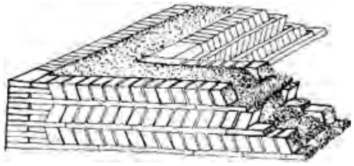
13.7 TURF CONSTRUCTIONS

Basic info is found in Chapter 10.

Structural walls of turf were once widely used in coastal regions of Northern Europe, such as in Ireland, Scotland, Wales and Iceland. Building in turf was also undertaken by immigrants to North America, especially amongst the Mormons who worked a great deal with this material after 1850. There are still a few turf houses in Iceland.

13.52

Traditional Icelandic dwelling with turf walls.
Source: Dag Roalkvam.



13.53

A turf wall contains layers of turf with earth between them. In the corners strengur turf is used; the rest of the wall is laid with knaus.
Source: Bruun, 1907.

Turf has many qualities, especially with respect to thermal insulation, but is no easy material to build with, and most of the alternatives such as timber, stone, concrete and earth are more durable and stable. But the question of economy and access to resources is also important.

A well-built turf house can have a lifespan of approximately 50 years, when the decomposition of turf will reach its critical point. Given good maintenance some examples have had a much longer lifespan. The durability is generally higher in colder climate.

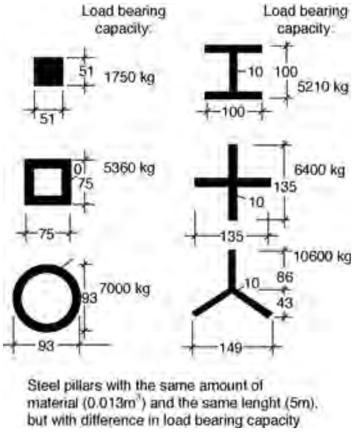
Icelanders worked with two qualities of turf, which they call *strengur* and *knaus.*

STRENGUR AND KNAUS

Strengur is the top 5 cm of the grass turf and is considered the best part. It is cut into large pieces that are laid in courses on the foundation walls. Knaus is from deeper levels and is of a lower quality. These are smaller pieces of turf, approximately 12.5 cm thick, which are laid according to the 'Klömbruknaus' method (see Figure 13.53).

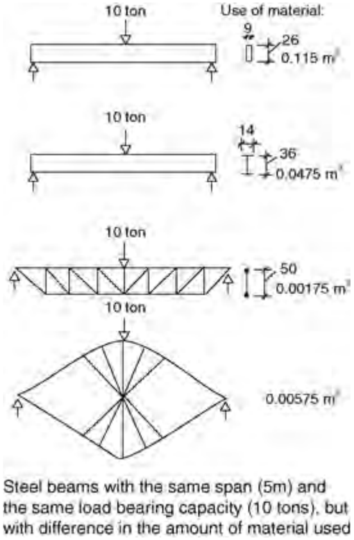
A problem with turf walls is the danger of them 'slipping out'. This can be reduced by stiffening the corners with stone or short timber dowels which can be rammed through the layers as the building progresses.

13.8 RESOURCE USE AND CLIMATE LOAD OF DIFFERENT STRUCTURAL SYSTEMS



13.54

Material use in steel pillars.
Source: Reitzel, 1975.



13.55

Material use in steel beams.
Source: Reitzel, 1975.

Every structural system has its own specific use of material, depending upon its strength. Solid structures of brick and concrete are highly intensive in their use of material, whereas timber and steel are usually more economical, but each material can also have different structural methods using different amounts of material.

Figures 13.54 and 13.55 show structural alternatives to pillars and beams. These examples deal with steel components, but the same principles apply for timber. One important aspect of structures with economical materials use is that they are often more labour intensive. The lattice beam with its many joints costs more to produce than the equivalent laminated timber beam, even if the use of material can be twenty times less. In some cases, however, the extra cost of transport and more intensive use of raw materials in the laminated alternative can change the economic equation quite drastically. It is also quite important that use of lightweight structures enables one to reduce foundations considerably (see Table 13.6). In cases where the soil is clay, weak or swampy this can be a particular advantage.

The energy use in the production of a structure is dependent upon the quantity of material used as well as the type of material. A comparison of the energy use for producing structural systems in different materials is given in Figure 13.56. In conclusion, a timber lattice beam is definitively the most energy-efficient alternative.

The embodied energy and sources of energy used will be directly reflected in the climate footprint of a construction. For concrete, steel and aluminium one must add the materials related chemical emissions during production. Eventual re-absorption of carbon dioxide into concrete must be subtracted, and in the case of timber the carbon bound can be subtracted too. Ultimately there is little doubt that timber constructions come out very favourably (Goverse *et al.*, 2001; Petersen *et al.*, 2002; Kram *et al.*, 2001; Graubner, 1992, etc). However, consideration relating to recyclability, thermal stabilizing properties (see Table 13.7), and durability will naturally also come into play, and perhaps even be of prime importance.

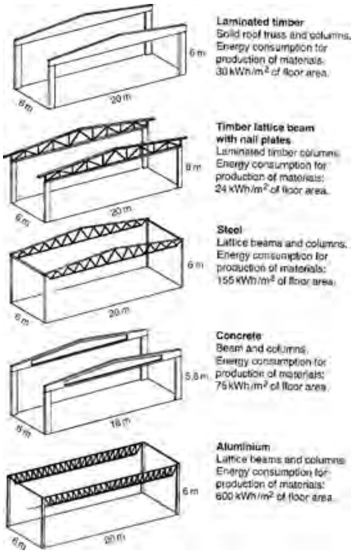
Comparing lightweight and massive timber construction is quite a complex issue. If carbon storage is important then this gives an added

Table 13.6 *Foundation requirements for different constructions and soils*

Construction weight	*Marsh to soft clay (kg concrete/m^2)*	*Firm clay to sand & gravel (kg concrete/m^2)*
Light (wood and steel)	150	100
Heavy (brick and concrete)	250	100

(Source: Gielen, 1997).

advantage to the latter. On the other hand long transport distances will weigh against massive timber.



13.56

Comparative calculation of energy needed to produce different structures. The aluminium alternative is produced from ore.
Source: NTI, 1990.

ENVIRONMENTAL PROFILES OF STRUCTURAL MATERIALS

READING GUIDELINES FOR TABLE 13.8:

The estimates and evaluations are made per m^2 of floor space and a house lifespan of 50 years. All materials are assumed to last this long without renewal.

The volumes of materials and the loss factors are estimated on the basis of conventional practice.

The effects of additional material properties, such as thermal storage capacity and thermal conductivity, are not included.

Calculation of global warming potential GWP include carbonatation (50 years), storing of carbon dioxide (50 years) and emissions from final incineration of products based on fossil fuels. The storing of carbon is calculated from net weight of material (exclusive losses).

The environmental evaluations are rated with best = 1, average = 2 and worst alternative = 3. The *Environmental potential* columns indicate potentials for recycling and local production. The final environmental profile is suggested on the basis of subjective judgement from the author and is open to debate. On the basis of information in Table 1.4 and Table 2.8 alternative evaluations can be made. Also note the results in the GWP column, since global warming potential is often considered as a relevant overall indicator for environmental impacts.

Table 13.7 *The impact of building weight on energy demand for heating, location in Central Europe*

Outer/inner structure	*Single family dwelling %*	*Multi family dwelling %*	*Office building (with cooling) %*
Light/light	100	100	100
Light/heavy	85	94	94
Heavy/light	95	100	98
Heavy/heavy	103	103	93

(Source: Kram et al., 2001).

Table 13.8 *Environmental prefiles of structural materials*

Material	*Compressive strength (kp/cm^2)*	*Tensile strength (kp/cm^2)*	*Loss factor (%)*	*Quantity needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO_s-equ./ m^2 50 years)*	*Environmental evaluations*						
						Effects on resources		*Effects of pollution*		*Environmental potential*		*Environmental profile*
						Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Horizontal structures												
Steel beams, recycled	5400	5400	5	40	**42**	3	2	2	3	√		**2**
Aluminium beams, 85% recycled	4300	4300	5	15	**49**	3	3	3	3			**3**
In situ concrete, reinforced	150–700	7.5–35	15	460	**73**	2	3	2	2		√	**2**
Precast concrete elements	150–700	7.5–35	7	405	**66**	2	2	2	2	√	√	**2**
Aerated concrete elements	30	4–5	7	135	**34**	2	3	2	2	√		**2**
Light aggregate concrete elements	30	4–5	7	200	**62**	2	3	3	2	√		**3**
Wood beams, untreated	450–550	900–1040	15	47	**–21**	1	1	1	1	√	√	**1**
Wood beams, laminated	470	1040	7	37	**–2**	1	1	2	2			**2**
Massive wood elements, untreated	450	900	7	110	**–53**	1	2	1	1	√	√	**1**
Vertical structures												
Steel studwork, recycled	5400	5400	5	30	**31**	3	2	2	3	√		**2**
Aluminium studwork, 85% recycled	4300	4300	5	10	**32**	3	2	3	3			**3**

Table 13.8 *(Continued)*

Material	*Compressive strength (kp/cm^2)*	*Tensile strength (kp/cm^2)*	*Loss factor (%)*	*Quantity needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO_s-equ./ m^2 50 years)*	*Environmental evaluations*						
						Effects on resources		*Effects of pollution*		*Environmental potential*		*Environmental profile*
						Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
In situ concrete	150–700	7.5–35	15	400	**65**	2	2	2	2		√	**2**
Precast concrete elements	150–700	7.5–35	7	275	**45**	2	2	2	2	√	√	**2**
Aerated concrete blockwork	30	4–5	10	180	**42**	2	2	2	2			**2**
Light aggregate concrete blockwork	30	4–5	10	240	**75**	2	3	3	2			**3**
Lime sandstone	150–350	7,5–17,5	11	240	**36**	2	2	2	2			**2**
Granite, sandstone, gneiss	200–2000	100–320	6	525	**5**	2	2	2	1	√	√	**1**
Gabbro, syenite, limestone	200–5000	160–315	6	525	**5**	2	2	1	1	√	√	**1**
Earth, compressed	40	6	2	820	**16**	1	2	1	1	√	√	**1**
Well-fired bricks, massive	325	33	10	460	**87**	2	3	3	2	√	√	**2**
Well-fired bricks, perforated	325	33	10	410	**78**	2	3	3	2	√	√	**2**
Wood studwork, untreated	450–550	900–1040	15	10	–**5**	1	1	1	1	√	√	**1**
Massive wood	450	900	7	90	–**44**	1	2	1	1	√	√	**1**

13.57

Roof construction of laminated wood at Gardemoen Airport, Oslo. If an alternative with steel had been chosen the emission of greenhouse gases in manufacture would have been 5 times higher (Petersen et al. 2002). Architects: Aviaplan, 1998.

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14 Climatic materials

Climate regulating materials control the indoor climate, and are mainly orientated towards comfort. They can be subdivided into four groups:

- temperature regulating.
- air regulating.
- moisture regulating.
- noise regulating.

Temperature regulating materials include thermal insulation materials built into the outer walls and roof, as well as materials that reflect heat radiation or stabilize room temperature through high thermal capacity. The main reasons for using temperature regulating materials are to increase thermal comfort and reduce energy use for space acclimatization (heating and/or cooling).

Air regulating materials are usually composed of thin barriers covering the complete building envelope to resist air flows through the construction. The three major motives are to increase the thermal comfort for the inhabitants, reduce the risk of moisture problems and reduce the energy needed for space acclimatization. Air barriers are also used in internal walls between cold and warm rooms, where there is a chance of a draught being caused in the warm room.

Moisture regulating materials are used for waterproofing, and to prevent vapour produced from people and processes inside the building from penetrating walls and roof and creating moisture problems, especially through condensation. They also include materials that can regulate and stabilize moisture both within the construction and in the indoor air.

Noise regulating materials are necessary to reduce transfer of sound of different types both in and between rooms, as well as between inside and outside, and to provide a good acoustic climate.

Certain climate regulating materials have qualities that put them in two or three of these groups (Table 14.1). A thermal insulation material can also be airtight, regulate moisture and even stop noise. Different functions can also be combined, e.g. timber can be a moisture-regulator while acting as a structural and surface material.

Table 14.1 *Climatic materials in building*

Material	*Thermal regulation*		*Air regulation*	*Moisture regulation*		*Noise regulation*
	Insulation	*Buffering*	*Tightening*	*Tightening*	*Buffering*	*Insulation*
Snow	Lu					Lu
Metals, sheets and foils	Lu		Lu	Gu		
Foamed concretes	Lu					
Aerated concretes	Gu				Lu	Gu
Concretes with light aggregate	Gu					Gu
Gypsum boards		Gu	Lu		Lu	Gu
Fossil meal	Nu				Nu	Nu
Perlite	Gu					Gu
Vermiculite	Lu					Lu
Silica aerogel	Nu					
Foamglass	Gu			Lu		
Mineral wool	Gu					Gu
Montmorillonite				Gu		
Low-fired bricks		Lu			Lu	
Light expanded clay pellets	Gu					Lu
Earth plaster		Lu			Lu	
Bitumen products			Gu	Gu		
Plastic mastics and sealing strips			Gu	Gu		
Plastic sheets and foils			Gu	Gu		
Foamed plastics	Gu					
Loose fill from plant fibres and cellulose	Gu				Lu	Gu
Matting from plant fibres and cellulose	Gu				Lu	Gu
Boarding from plant fibres	Gu		Gu		Lu	Gu
Loose fill and boarding from peat	Nu				Nu	Nu
Paper from cellulose			Lu			
Matting from wool	Lu				Lu	Lu
Matting from recycled textiles	Lu				Lu	Lu

Note: Construction materials that quite often will possess good thermal stabilizing, moisture buffering and sound insulating properties, are not included in the table. This also goes for surface materials used for interior cladding which are important moisture buffers.
Empty spaces indicate that use is irrelevant.
Abbreviations: Gu: In general use; Lu: In limited use; Nu: Not in use

TEMPERATURE REGULATING MATERIALS

Thermal insulation

The main part of this chapter considers the properties of different materials in relation to static insulation.

The technical demands of an insulating material are usually as follows:

1. High thermal insulation properties.
2. Stability and long lifespan.
3. Fire resistance.
4. Lack of odour.
5. Low chemical activity.
6. Ability to cope with moisture.

The thermal insulation property for static insulation is usually called lambda (λ) and can be measured with special equipment:

$$\lambda = \mathrm{W}/(\mathrm{m}^\circ \mathrm{k})$$

Mineral wool has a lambda value of 0.04, whilst a woodwool slab has a value of about 0.08. This means that a double thickness of woodwool gives the same insulation value as a single thickness of mineral wool. However, there is not always a linear relationship between the lambda value and the practical insulation value. The material's specific weight, hygroscopic quality and air resistance play a role too.

STATIC AND DYNAMIC INSULATION

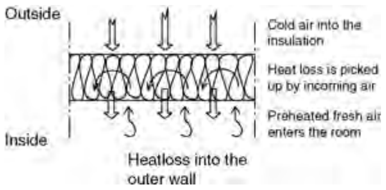
The thermal insulation of a building can be done in two ways: as *static* or *dynamic* insulation.

In *static insulation* the insulation value of still air is used. The principle requires a porous material with the greatest possible number of small air pockets. And these have to be so small that the air does not move inside them. Most insulation materials are therefore foamed or fluffy materials that are mostly air.

Dynamic insulation is a little-used approach. Here air is deliberately drawn through a porous insulation material. When cold, fresh air is led from outside through the wall, rather than through ventilation ducts, it picks up heat loss flowing out of the building (Figure 14.1). Besides achieving a preheated fresh air flow into the building, the outward heat loss through the surfaces is reduced to a minimum. The optimal materials for such a wall should have an open structure with pores across the whole width, plus good heat exchange properties. A high thermal capacity is also an advantage, so that sudden changes in the outside temperature are evened out. Dynamic insulation is still being introduced into construction and has been used in only a few buildings (Figures 14.2 and 14.3).

Ageing can also affect the insulation value. Certain products have shown a tendency to compress through the absorption of moisture and/or under their own weight, whilst others may shrink (mainly foamed plastics). The thickness of the layers of insulation needs to be appropriate for the local climate. Some humidity will always get into a wall, and too much insulation can cause the temperature to be too low in the outer part of the wall; thereby reducing any drying out. This can lead to fungus developing in the insulation or adjoining materials. This is primarily an issue in the new low energy buildings, such as the extremely well insulated 'passive houses'.

Insulation materials are manufactured as loose fill, solid boards or thick matting. The latter two can occasionally result in a ruptured layer of insulation since temperature or moisture content changes can cause



14.1

The principle of dynamic insulation.

Source: Torgny Thoren.

14.2

Dynamic insulation in the roof of the swimming pool at McLaren Community Leisure Center in Callander. Architects: Gaia Scotland, 1998.

dimensional changes. This is especially the case with solid boards, which need to be mounted as an unbroken surface on the structure and not within it. Loose fill insulation is good for filling all the spaces around the structure, but it can settle after a time. The critical factors are the density and moisture content of the insulation. The disadvantages of hygroscopic materials become apparent here because they take up more moisture and become heavier. Settling, which is seldom more than a small amount, can be compensated for by using elastic materials which have a certain 'suspension' combined with adequate compression. Structures with hygroscopic loose fill as insulation may need topping up during the building's lifespan.

Thermal insulation materials usually occupy large volumes, but they are light and seldom take up more than about 2% of the building's total weight. Many of the most common commercial insulation products are derived from fossil oils. Plant-based materials are, however, now attracting more attention. Many of the commonly used insulation products have quite high embodied energy and associated greenhouse gas emissions. In addition, foamed plastics are often made using hydrofluorocarbons (HFCs) as foaming agents, and these are very powerful greenhouse gases. There is also a variety of environmentally problematic additives in many insulation materials, including synthetic glues, flame retardants and fungicides. For these reasons the waste materials must often be specially handled. Only in exceptional circumstances is it possible to recycle or re-use insulation materials.

14.3

Barn with hay performing as dynamic insulation in the roof of the stable through the winter period. At the same time the hay is used as fodder and by the end of spring everything is eaten up. And in autumn fresh hay is refilled. Lillehammer (Norway), Gaia Arkitekter, 1995.

Thermal stabilization

During the winter months, a building in heavy materials will store heat from warm rooms and return it when the room temperature goes down. In this way heavy materials stabilize the indoor temperature, and in summer maintain a cooling effect. This effect increases comfort and can reduce energy needs significantly; while at the same time

Table 14.2 *Thermal storage capacity and thermal diffusivity of selected materials.*

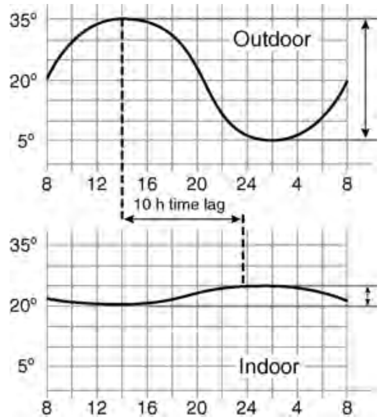
Material	*Specific weight [kg/m^3]*	*Thermal storage capacity [kJ/m^3 K]*	*Thermal diffusivity [10^{-4} m^2/h]*
Concrete	2400	2100	24
Brick	1500	1260	22
Massive wood	500	1150	4
Wood fibre board	180	415	4
Mineral wool	16	12	48

The thermal storage capacity decribes the maximum heat storing capacity of the material, not the actual speed of the uptake. Materials with both high thermal storage capacity and high thermal diffusivity will quickly respond to changes in temperature and therefore effectively buffer overheating in the interior. Materials with low thermal diffusivity will ensure that the flow of warmth from the exterior to the interior on a hot summer day is adequately dampened, see Figure 14.4.

depending on the building's mode of heating, function, user habits and the local climatic conditions (see Figure 13.7).

The thermal stabilizing properties depend first of all on the materials. The key factors are *specific weight*, *specific heat capacity* and *specific thermal conductivity*. More practical terms are *thermal storage capacity* (specific weight × specific heat capacity) and *thermal diffusivity* (thermal conductivity/thermal storage capacity) (see Table 14.1 and Figure 14.4). In general, the outer layer of about 10–20 cm can be activated during a 24 hour cyclus. Location of the heat storing parts is also important. Interior walls, ceilings and the inside surface of the outer walls are most useful. The heat-storing surfaces will act less effectively if obstructed by wallpaper, hangings or large furniture.

There have been efforts to increase the heat storing capacity of wall materials by adding phase change materials (PCM) (Silva, 2007; Fossdal, 1995). These are usually fairly simple salt hydrates and react exceptionally quick to temperature changes.



14.4

The variation of temperature during 24 hours on a hot summer day with a wall insulated with wood fibre boards, see Table 14.2. The time lag for the outside heat to penetrate the wall is substantial and the temperature will not reach a maximum before midnight. After that the heat can easily be exchanged with cold night air through conventional ventilation.

Source: Gutex.

Heat-reflecting materials

By mounting a material that has a low reflectivity for short-wave solar radiation on a building's façade, solar energy can be captured very efficiently, whilst a sheet of highly reflective material on the inside of the wall will reduce heat loss outwards. This is especially utilized in modern window technology. They let in a maximum of heat, but only let a minimum escape, and they can be used in the opposite way in hot climates (Table 14.3).

Also commercially available are reflecting foils, sometimes made up of several layers, which can be used in walls or roof spaces. There must be an air gap on either side, if small, and the reflecting surfaces must be kept free of dust. The reflecting foil eliminates virtually all transfer of radiant heat; however, heat loss by conduction still requires a layer of normal static insulation.

AIR REGULATING MATERIALS

Air movement is normally addressed in two areas in a wall or other parts of the building envelope. Towards the outside there is a *wind-proof layer*. On the interior there is an *air barrier* that adds to the wind-proofing

Table 14.3 *The approximate reflection of heat radiation from different surfaces*

Material	*Reflection [%]*
Shiny aluminium	70
Aluminium bronze	45
Brick	14
Timber	14
White paint	70
Black paint	1

and ensures that there are no significant air leaks, which increase a building's energy use considerably. Leakage points also dramatically increase the risk of humidity damage inside the walls, where humid warm air leaks out to a cold spot and condenses there (Morgan, 2006). Air barriers in buildings usually combine their function with that of vapour membranes. Although the primary function in climatic terms is as an air barrier, this construction feature is discussed in the section on *moisture regulating materials* (see page 245), according to procedures in conventional building physics.

The wind-proofing of a building should be addressed at two levels: the first is that of good site planning and sheltering with trees and hedges; the second is at the level of the construction itself.

THE EFFECT OF LANDSCAPE AND VEGETATION

By careful site planning and screening with fences, trees and hedges the amount of wind reaching the building envelope can be much reduced. If the average wind speed around a building is reduced by 1 m/s, this alone can reduce the energy requirements for space heating by 3%. In the Norwegian coastal town of Kristiansund, where the average wind speed is 22 km/h (Beaufort scale 4), the loss of heat for an unscreened building through infiltration is 40% greater than for a screened building.

There are several available constructive means to reduce the infiltration of wind into the main body of a building:

- Wind breaking structures.
- Wind breaking textures.
- Wind barriers.

Wind breaking structures

A windbreak structure should be perforated and preferably be on battens at a distance from the actual wall. By using about 30% perforation, a minimal difference of pressure between the front and the back of the screen is achieved. The formation of eddies is thus reduced, so that wind and rain are effectively slowed down. Suitable materials include climbing plants, trellises, timber battens or metal ribbing.

Wind breaking texture

A wind breaking texture is mounted directly on the main wall, in the form of a rough-structured surface that causes countless minute air movements – a sort of air cushion. The wind is stopped dead instead of penetrating further into the wall. Effective materials for this are roughly-structured render, cladding made of branches or a living surface of plants, including conventional creepers.

Wind barriers

Neither external windbreaks nor texturing has any effect on air infiltration as a result of suction forces. The wind protection, therefore, needs to be complemented by a wind barrier in the outer layers of the wall construction itself. This is normally behind the external cladding and is itself ventilated. Suitable materials include exterior quality plasterboards, boards of wood fibre, and various papers or asphalt impregnated sheeting.

To this, sealants and mastics around windows, door openings and other joints have to be added. These latter products are often plastics-based, hence oil products, and may have far more limited lifespans than is often assumed. This is especially the case on south façades where they are exposed to solar radiation and large diurnal temperature variations. These joints are often difficult to inspect or improve. The best solution is to avoid the need for these as far as possible through careful cutting and fixing of the building elements – good carpentry – and by having overlaps in the wind barriers that are fixed tightly with small battens.

Wind barriers should not let through air more than 0.1 m^3/m^2 with a pressure of 10 Pa. In extremely windy conditions such as heavy storms or hurricanes, it is very difficult to prevent wind penetrating the building. In exposed locations it would be best to use heat insulation materials with good wind-proofing properties as well, e.g. well-compressed loose-fill wood fibre.

MOISTURE REGULATING MATERIALS

Moisture should not be able to force its way into a building's structure without being able to get out again. Apart from the dangers of mould and rot within organic materials, the dampness can freeze and cause the breakdown of mineral materials when frost occurs. Damp also reduces the insulation value of the materials drastically. Moisture can enter a structure in six ways:

- As moisture released from the building materials.
- As ground moisture.
- As rain.
- As water spilled in bathrooms or kitchens.
- As airborne moisture from inside or outside.
- As moisture from installations that leak, such as drains, water supply or heating systems.

The last point does not need to be discussed, since it depends on good execution and technology alone. Humidity requires special consideration in the case of highly insulated buildings. A wall with 250 mm of insulation will take 70% longer to dry out than a wall with 150 mm insulation (Folleràs, 2007).

Moisture within building materials

During construction, a new house may contain about 10 000 litres of water within its building materials. Drying time for these is strongly dependent upon the structure of the material. There is an unnamed relative material factor, *s*. The drying capacity of a material increases when this factor value falls. Lime mortar has an *s*-factor of 0.25, brick 0.28, timber 0.9, lightweight concrete 1.4 and cement mortar 2.5.

To avoid moisture, materials should be carefully kept in dry storage at the building site. Ideally one may cover the whole building, so-called Weather Protection Systems (WPS); other systems enable one to complete the roof covering well before the other parts.

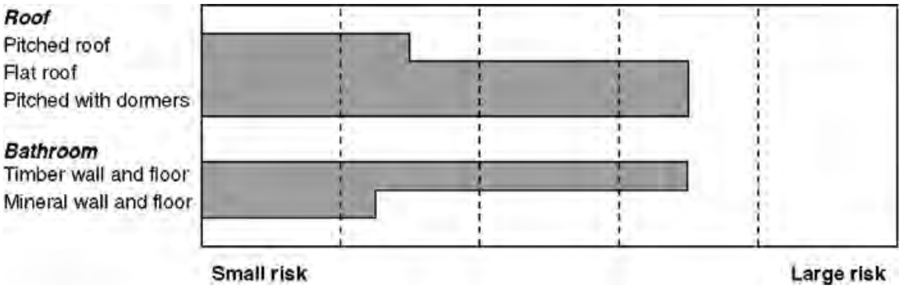
Concrete, earth and timber structures should be allowed to dry out before they are used with less moisture-diffusive coverings or surface treatments. Many defects, for example, arise from insufficiently dried concrete being covered by PVC or other impermeable layers so that the humidity is effectively trapped and cannot dry out.

Ground moisture

A building site should be dry and well-drained. However, foundations are exposed to dampness throughout their lifetime. This can be reduced by adding something that breaks the capillary action of water rising from the ground: for example, a layer of broken stone (hard core), expanded glass or clay aggregate, or else heavy grade plastic sheeting. It is common for structures to have a damp-proof course between the foundation and the rest of the structure; usually a layer of bitumen felt placed along the base of the wall a short distance above ground level, but below the level of the interior floor. High quality slate, slabs of granite, etc. may also be used. It is nonetheless difficult to prevent a certain amount of moisture entering the fabric of the building. This will increase as the damp-proofing course ages. There have been a series of damp problems associated with organic floor coverings such as timber, vinyl sheeting, etc., that were laid directly on concrete in slab-on-grade constructions, even where there is a plastic membrane in between. As insurance against such problems, concrete slabs on the ground should preferably have mineral floor coverings such as slate or ceramic tiles.

Rain

External cladding and roof coverings is discussed in greater detail in Chapter 15. There is also a need for special components to protect exposed parts of the building; in particular the critical points where chimneys, pipes, ventilation ducts, roof lights and so on penetrate the building fabric. Roof gutters and downpipes are also critical; these are often made of heavy plastics or metal sheeting, either prepared on site or prefabricated. All these points are subject to exceptional weathering. The fact that they need inspection and replacement more often than most other external components is often overlooked. It has been documented that buildings with rooflights and other roof protuberances have a considerably higher risk of water damage



14.5

Risk of moisture damage in different constructions. Results from an investigation of 16 000 Danish houses.
Source: Valbjørn, 2001.

(Valbjørn *et al.*, 2001) (Figure 14.5). The same applies to flat roofs, especially in rainy climates. This is primarily due to incorrect design choices, no matter what materials are used.

Water spills

In bathrooms and kitchens there is often a lot of water spilled. Water penetration is prevented by waterproof membranes. These are most often of bitumen or plastics. Their lifetime is coinsiderably shorter than that of the building, and they are difficult to inspect and often concealed behind other layers. It has been shown that damage is less common with the use of pure mineral constructions for bathroom floors; and even less common when mineral materials are also used in walls (Valbjørn *et al.*, 2001) (Figure 14.5).

Air moisture

Air moisture is almost entirely produced inside the building by people, animals and plants, or from cooking and using bathrooms. The building

14.6

Interior wooden and rendered surfaces with high moisture buffer capacity. Gaia Lista, 2007.

itself gets damaged when air moisture penetrates the external walls and condenses there.

AIR'S MOISTURE CONTENT AND CONDENSATION RISK

The lower the temperature, the less water vapour air can hold. At 20 °C air can hold 14.8 g/m^3 of water vapour, while at 0 °C it can only hold 3.8 g/m^3. If the internal air at 20 °C only holds 3.8 g/m^3, it can pass through the wall to outside air at 0 °C without any condensation being formed; but if the air is saturated with 14.8 g/m^3 then there can be condensation within the wall of 11 g/m^3. In normal circumstances a room contains about 5–10 g/m^3 of water vapour, whilst, for short periods, a bathroom can contain almost 14.8 g/m^3.

Major condensation problems can occur around air leakages in walls and roofs, especially in winter when the outer parts of the walls are colder. At the same time, moisture diffusing through unbroken layers of materials normally takes place without large amounts of condensation being formed inside the wall. A wall completely free of small cracks is unrealistic, so it is necessary to take certain precautions using the following principles:

- Vapour membranes.
- Moisture buffering materials.

Vapour membranes

The humidity strategy and use of vapour membranes must be seen in conjunction with air tightness. They are most often combined in one single layer, mounted continuously and without perforations, immediately behind the interior surface cladding. Whilst the vapour membrane should ensure that humidity cannot penetrate the construction, the air barrier should prevent cold air from entering, which, in turn, encourages condensation.

The *vapour barrier* is highly vapour-proof and is now a widely used approach. The theory is that it should totally prevent water vapour from entering the wall; all indoor vapour should instead be controlled and extracted by a ventilation system. In practice, however, this method has certain weaknesses. The only usable materials for this purpose are plastic sheeting or metal foil. How long these materials will last is an unknown factor. During the building process, rips, holes and such will inevitably be caused. At these points, small amounts of vapour will creep through, and after a time condensation will occur in the wall.

A more moderate and less vulnerable solution is a *vapour retarder* that limits vapour diffusion. This is not as absolute as vapour-proofing, but reduces penetration considerably. Materials used for this are high-density fibreboards and different types of robust cellulose and plastic-based sheeting. The choice of material is determined by the type of wind-proofing used on the outside of the wall. A rule of thumb is that the resistance to vapour diffusion on the inside must be four to five times higher than the wind-proofing layer on the outside to give the vapour a direction (Adalberth, 1998). In this type of wall, humidity can travel through without the risk of condensation. It is important to note that the windbreak's resistance to diffusion is often heavily reduced if it is damp – down to 10% of its original value in the case of a porous wood fibreboard. It is therefore often possible to use the same material on both sides of the wall.

The combined vapour membrane/air barrier is a critical element in a building envelope. The material must be robust and long-lasting; and all holes in it must be avoided through careful detailing as well as very conscientious execution on site. Where there is thick wall insulation, this is often aided by not placing it immediately behind the wall surface, but behind the first layer of say 5 cm of insulation. This reduces the risk of later holes being made when users hang pictures or other items. At the same time, many of the pipes and the electrical conduits can be placed in this inner layer so that they too do not have to go through the membrane.

Membranes are often jointed with tape. This may well become brittle after only a few years. It is much better to overlap the membrane sheets and nail them to the underlying structure with a thin wooden batten covering the whole length of the overlap. Taped solutions can fail after as little as 1 to 3 years (Bøhlerengen, 2002).

Moisture buffering materials

Many materials used in building interiors are hygroscopic. This means that they have the capacity to absorb some humidity and then release it later when there is less humidity inside the building. In this way they can deal with excess humidity and even out the fluctuations.

A stable humidity level indoors is healthy as well as reducing loads on the vapour barrier. Untreated wooden panelling in a bathroom is an example. When the bath is being used, the panelling absorbs much of the water vapour produced. Afterwards, when the bathroom is left, the air dries out quickly as a result of the background ventilation. The panelling then releases the absorbed moisture back into the air of the room. The whole process takes place without the need of any mechanical ventilation and therefore also has a substantial energy-saving effect. A similar situation is created when the occupants of a house go to bed or leave for work: the moisture content in a living room with hygroscopic walls will be stabilized. Even if the temperature often falls during this period, the process still continues.

The use of hygroscopic materials is also proving to be important for construction and insulation materials. This is because there will always be some uncontrolled moisture leakage, either from outside or inside, during a building's life, both due to defects, ageing and movement of materials that may be caused by differential settlement, wind or even earthquakes. In addition, these will often be invisible. It is, therefore, a great advantage if all of the main materials have some hygroscopic ability. When damp occurs they will be able to regulate it and avoid mould or rot damage. In dry summer weather, they can return the moisture to the environment. Insulation materials with good hygroscopic qualities include most of the plant based types, whilst mineral wool and plastics based types are almost completely without hygroscopic capacity. Structures of timber and earth are very hygroscopic, concretes much less so and metal ones not at all.

shown that this effect takes place naturally when the ventilation ducts in the building fail for some reason. The effect is called gas diffusion – not to be confused with lack of air tightness.

The vapour membrane layer, even if very open to moisture, is always air tight. Gas diffusion occurs following the principle that gases always tend to spread themselves evenly in the surroundings. In a wall open to gas diffusion, the different gases travel in both directions – oxygen coming in and carbon dioxide going out – the speed determined by pressure conditions and the molecular weight of the gases involved (see Chapter 4).

Tests have been carried out in Finland on stud wall constructions with a vapour retarder and wood-based insulation materials. They showed that considerable amounts of water vapour molecules (H_2O) migrate through the wall when air change rates are reduced to a minimum; and this happens without the risk of moisture damage (Simonson *et al.*, 2005). There is also considerable diffusion of other light molecules such as CO_2 whilst movement of heavier molecules, including some pollutants such as organic solvents, is slower but still occurs. At the same time, oxygen is seen to migrate in the opposite direction, from outside inwards. For example, a 20 cm thick brick wall with an area of 10 m^2 lets in about 90 litres of oxygen each hour under normal pressure. This is the equivalent of one person's requirements in the same period. The conditions for this calculation are that the oxygen content for outside air is 20% and for inside air it is 15%.

By increasing the porosity of the wall surface the 'breathing' of gases will increase and the heavier molecules will also diffuse more easily. This involves increasing the permeability of the wind-barrier and vapour membrane. This requires good control of the temperature and pressure conditions, which can be facilitated by placing a building within as semi-acclimatized envelope such as a glazed outer zone.

NOISE REGULATION

Materials for noise regulation are used partly to abate noise between rooms within a building, or between inside and outside areas, and partly as absorbers or reflectors within a single room.

Sound barriers normally consist of heavy materials that block the passage of sound waves. An effective example is turf roofs in the vicinity of airports. Sound barriers are normally part of the construction itself, such as a concrete wall between apartments, but layers such as heavy plasterboard can also be added. Sound barriers should be complemented by effective sound absorbers. Most porous insulation materials can be used. In floors, good sound barriers can be provided by loose filled sand. However, while these materials can provide acoustic insulation against the higher frequencies – such as conversation, one must also provide sound insulation against step sound and other noise transmitted through the structure. To achieve this sufficiently, construction often has to include a floating layer or partitions that are not physically in direct contact with each other.

Noise absorption within a room involves suppressing echoes, reveberation and resonance, whilst reflection involves directing the sound waves to where they are wanted. Absorbers and reflectors are primarily a design issue; room volumetry and textures are central factors. Acoustic brick walls, for example, have perforated brick surfaces exposed towards the room. Acoustic ceiling panels and hanging sound baffles are also often used. Fairly simple solutions such as woodwool cement slabs fixed or suspended from classroom ceilings are often seen. Lightweight insulation is also often used in combination with perforated plasterboard or other perforated wall cladding.

Because of their porosity, small holes, etc., acoustic materials will often collect dust. Exposed ceilings of mineral wool have been registered as shedding fibres, leading to serious indoor climate problems.

In general, most acoustic materials will simultaneously have other functions in a building, e.g. as construction materials and thermal insulation. The discussions concerning these materials will therefore be somewhat decentralized in this book.

14.1 SNOW AS A CLIMATIC MATERIAL

Basic info is found in Chapter 5.

Snow is a light material that consists mainly of small air spaces; it is therefore a good insulator. The thermal insulation of dry snow is equivalent to that of rockwool, and this is reduced with increased water content.

Over large areas in Northern Europe, dry snow settles every winter and remains for about six months, helping with roof insulation just when it is most needed. So it is clear that this snow should be conserved. There are six ways of retaining snow on a building:

- A sloping roof of not more than 30°, preferably less.
- A roof covering made of high friction material, such as grass.
- A snow guard along the foot of the roof.
- An unheated space under the roof, or else very good roof insulation.
- Windbreaks in front of the roof.
- Reduced solar radiation on the roof, for example a single pitched roof facing north.

Some of these conditions have disadvantages. But snow is free, and it is an efficient and environmentally friendly insulating material. The thermal insulation of snow should certainly be considered when designing in areas where white winters are common. However, these regions look set to dwindle as a result of global warming. Regions with mild winters and few snow days do not need snow planning; the same goes for sites exposed to heavy wind, but in many cases well-planned placing of snow drifts can provide excellent protection from wind. This can be done using special snow fenders with an opening of approximately 50% in the grid, and also with the help of planted hedges and avenues. Snow will settle on the lee side in areas of turbulence.

14.2 METAL-BASED MATERIALS

Basic info is found in Chapter 6.

For climatic purposes metals are commonly used for flashings. Flashing is used on exposed parts of a building's external skin, such as between the roof and parts that penetrate the roof such as chimneys, ventilation units, vent stacks and roof lights, and on valley gutters and

14.7
A wooden gutter produced in heartwood of pine.

snow guards. Not all metals are usable as flashing, as some corrode. Combinations of different metals can create galvanic corrosion.

Metals are also used in vapour barriers and heat reflecting surfaces. These are often aluminium products. In vapour barriers, an aluminium foil is often laminated on to a building paper. Heat-reflecting sheets are often reinforced with films of polyethylene and often comprise up to six layers, with layers of foamed plastic in between, though wool can also be used.

Stainless steel sheeting is produced from an alloy with chrome and nickel. In aggressive environments an addition of molybdenum is also found. Stainless steel can be used in combination with other metals.

Galvanized steel sheeting needs about 275–350 g/m^2 zinc. The material should not be used with copper. Gutters are often coated in plastic.

Aluminium sheeting normally has 0.9–1.4% manganese in it. The products are often covered with a protective coating through anodizing. They can also be painted with special paint. They should not be used in combination with copper or concrete.

Copper is usually produced in a pure form without any surface treatment or other alloyed metals.

Zinc is most often used in alloys with copper and titanium, and should not be used in combination with copper.

Lead is soft and malleable. It should not be used in combination with aluminium.

In terms of raw materials, the use of metals should be reduced to a minimum. Flashings are very much exposed to the climate and therefore to deterioration. Zinc corrodes quickly in an atmosphere containing sulphur dioxide, which is common in towns and industrial areas; the spray of sea salt also causes corrosion. The zinc coating on galvanized steel is exposed to the same problems, but its durability is better in the long run. In particularly aggressive atmospheres even aluminium, lead and stainless steel will begin to corrode.

Production of metals is polluting and energy intensive. For the people using a building, metals are mainly neutral, even though a large amount of metal is assumed to strengthen the building's internal electromagnetic fields. Metal ions may also be released into the soil around buildings from weather exposed products. This can cause an environmental problem, depending on the amount and type of metal in question; lead and copper are the most troublesome. Metal can normally be recycled when it becomes waste, but this may be complicated by additives and coatings.

The best way to reduce use of metals on the outside of buildings is through a good design that avoids complicated roof forms and number of chimneys, roof windows, etc. Metal fittings on doors and windows can normally be replaced by high quality timber.

14.3 MATERIALS BASED ON NON-METALLIC MINERALS

Basic info is found in Chapter 6.

Many loose mineral materials contain natural pores that make them useful as thermal insulation. Examples are fossil meal, perlite and vermiculite.

Materials such as Portland cement, gypsum and lime are bad insulators, but they have the potential as binders for different mineral aggregates, to make them into blocks, slabs, etc. In the same way expanded clay pellets, pumice, wood shavings and woodwool can be bound.

Aluminium powder added to cement in a mixture of lime, gypsum and Portland cement acts like yeast and forms gas within the concrete. This becomes a lightweight concrete with good insulating and acoustic properties. It is also possible to foam up a relatively normal mixture of concrete using air pressure and nitrogen.

Quartz sand is the main constituent of glass and has a very high thermal conductivity, but glass can be foamed to produce a highly insulating and stable foam glass. Glasswool also originates from quartz sand. The sand is melted and drawn out to thin fibres and used as highly insulating matting or loose wool. A similar material, rockwool, is based on the rock species diabase and lime, treated in almost the same way.

Products containing larger amounts of gypsum or lime usually have excellent moisture regulating properties. Concretes based on Portland cement most often take up and release moisture very slowly. Damage can therefore easily occur to organic materials in direct contact with it.

Montmorillonite is a clay mineral well suited to waterproofing because of its high moisture absorption coefficient. Render containing sulphur also has a high waterproofing quality.

Most mineral insulation products have weak wind-proofing qualities, and require a separate membrane or skin such as render, timber panelling, or the equivalent.

These climatic products are based on materials from resources with rich reserves. What they nearly all have in common is that their extraction often causes a large impact on nature, damaging ground

Table 14.5 *Climatizing qualities of products from non-metallic minerals*

Material	*Composition*	*Areas of use*
Sand	Sand	Thermal buffering, sound insulation
Concretes[1]	Cements, water, aggregates	Thermal buffering, sound insulation
Cement-based boards and plasters[2]	Cements, water, aggregates	Thermal buffering, sound insulation
Foamed concretes	Portland cement, water, sand, tensides	Thermal insulation
Aerated concretes	Cement, water, lime, gypsum, quartz, aluminium powder	Thermal insulation, moisture buffering
Lightweight concretes with mineral aggregate	Cement, water, with fossil meal, expanded perlite, expanded vermiculite, expanded clay pellets, expanded blast furnace slag or crushed pumice	Thermal insulation, sound insulation
Lightweight concretes with organic aggregate	Cement, water, with wood chips, saw dust, hacked straw, cellulose fibre or polystyrene pellets	Thermal insulation, sound insulation
Lime based plasters[2]	Lime, water, sand	Thermal buffering, sound insulation, moisture buffering
Gypsum boards[2] and plasters	Gypsum, water. Boards are covered with a layer of cardboard and possibly added with silicon	Wind-barrieres, vapour retarders, sound-insulation, fireproofing, thermal buffering, moisture buffering
Calcium silicate sheets[2]	Silicon dioxide, water, lime, cellulose fibre	Sound insulation, fireproofing, thermal buffering, moisture buffering
Fossil meal, loose	Fossil meal	Thermal insulation
Perlite, expanded, loose	Perlite, possibly added with bitumen or silicon	Thermal insulation
Vermiculite, expanded, loose	Vermiculite	Thermal insulation
Quartz foam (silica aerogel)	Potassium waterglass, hydrochloric acid	Transparent thermal insulation
Foamglass	Glass (silicon dioxide, sodium carbonate, calcium carbonate etc.), manganese dioxide	Thermal insulation, damp-proofing
Glasswool	Quartz sand, soda, dolomite, lime, recycled glass, borax, phenol glue, silicone or aliphatic mineral oils	Thermal insulation, sound insulation
Rockwool	Coke, diabase, limestone, phenol glue, aliphatic mineral oils	Thermal insulation, sound absorption, sound insulation
Montmorillonite	Montmorillonite, usually between layers of cardboard	Damp-proofing

[1] Discussed in Chapter 13, Structural materials.
[2] Discussed in Chapter 15, Surface materials.

water and biotopes. The more highly refined products are, the more energy they consume in production, with associated pollution during the process.

Most mineral-based climatic materials are often chemically stable in the indoor climate. However, in many cases organic additives can cause problems by emitting irritating gases and encouraging the growth of micro-organisms. Some of the materials cause dust problems during the building process and even after the building is finished. Some raw materials include radioactive elements that lead to a higher concentration of radon in the indoor air.

As waste, mineral-based climatic materials can be considered chemically neutral; the main problem can be their volume. Attention must be given to coloured products, as the pigments may contain heavy metals.

Clean loose aggregates can be re-used, as can blocks and prefabricated units. They can also be crushed into insulating granules, which are particularly well suited to use as underlay for roads.

14.3.1 Cement products

Cement can be used as insulating material in three forms:

1. As foamed concrete.
2. As aerated concrete.
3. As binder for light mineral and organic aggregates.

Foamed concrete has considerably better thermal insulation properties than normal concrete, but still a lot less than conventional insulation materials. The lambda value is 0.1W/mK for densities of approximately 650 kg/m^3. It consists of Portland cement and fine sand in proportions of about half and half. The foaming agent is either tenside or protein substances. The latter can cause considerable problems in the indoor climate if they react with cement. Foamed concrete is seldom used in building construction because of its relatively low thermal insulation and low loadbearing capacity. It is used nowadays mostly for the levelling of floors, sprayed onto horizontal surfaces from mobile tanks transported by lorry.

Protein-based foaming agents are biologically degradable whilst this is only the case for about 80% of tenside products. Additional environmental aspects of this concrete are the same as for in situ concrete (see *The composition of concrete*, page 195).

Aerated concrete is produced by reacting finely powdered quartz (about 50% by weight) with lime, gypsum and cement. Fly ash can replace some of the lime. A yeast constituent such as aluminium powder is added to a proportion of about 0.1%. Aluminium reacts to release hydrogen. When the substance is almost stiff, it is cut into blocks and slabs that are hardened in an autoclave at 180 °C. Prefabricated slabs are usually reinforced with steel. Aerated concrete is the only commercial pure mineral block with good structural properties combined with high thermal insulation value. The material is very porous, and needs a surface treatment which is open to vapour, hydraulic lime render, for example. If the water content becomes too high the material will easily be cracked by frost. The production of aerated concrete is dependent upon aluminium. The total contribution of aluminium in the external walls of an average sized dwelling is 10 to 20 kg. Often this is recycled aluminium.

Quartz dust can be a problem during production. Aerated concrete normally has good moisture regulating properties and does not have any negative effects on the indoor climate, although the steel reinforcement can increase the electromagnetic field in a building. Aluminium will have completely reacted in the finished product, and in practice aerated concrete can be considered inert and problem free as waste. Both prefabricated slabs and blocks can be re-used, depending on how they were laid and the mortar used. Strong mortars are generally used which make it difficult to dismantle the components without damaging them. More appropriate mortars are weak lime cement mortar and hydraulic lime mortar. Crushed aerated concrete can be used as insulating granules for road building, and also as aggregate in lime sandstone, different light mortars and light concretes.

Concrete with light aggregate is usually produced as blocks, slabs or floor beam units and is relatively strong. There is a difference between products that have an organic and a mineral aggregate.

Mineral insulating aggregate in concrete can be pumice, fossil meal and light expanded aggregates of clay, vermiculite, perlite, recycled glass or blast furnace slag. Pumice, expanded clay, perlite and glass are the products best suited, as the others have a higher moisture absorption.

Sawdust and chopped straw can be used as organic constituents in concrete. Blocks are also produced using broken up waste polystyrene, and it is possible to produce lightweight concrete mixed with waste paper. With the exception of woodwool slabs (discussed later in this chapter in the 'Timber'-section), concrete with organic constituents generally has a poor thermal insulation value compared to rival products such as aerated concrete.

Raw material for concrete with light aggregate is widely available. The pollution and energy use caused by the production processes are quite similar as those for constructional concrete, see Chapter 13.

Except for possible pollution from the additional use of insulation based on fossil oils in some products, the use of concretes with light aggregate usually causes no problems.

Lightweight concrete blocks can easily be re-used if they are held together by weak mortars, as can larger concrete units that have been bolted or placed without fixing.

Concretes with most light aggregates are initially inert and the waste from them can be used as a filler for road building, as ground insulation or as insulating aggregate in smaller concrete structures, light mortars and plaster.

14.3.2 Gypsum products

Gypsum is used mainly for soundproofing and wind-proofing boards and these are also good moisture regulators. The products are cast from 90–95% gypsum which has fibreglass added (0.1% by weight) as reinforcement. The following constituents are also usually added, to a total weight of 1%: calcium lingo-sulphate, ammonium sulphate and an organic retardant. In the wind-proofing boards the additives include silicone (0.3% by weight). The boards are often covered in cardboard glued with a potato flour paste or polyvinyl acetate (PVAC). Acoustic boards have a covering of woven fibreglass on the surface.

Gypsum is sourced both from coal-fired power stations as a by-product and from nature. In both cases, raw material availability is good, even if it is hoped that polluting coal power stations become less common in future. However, it should also be noted that the extraction of natural gypsum often has a large impact on the local natural environment.

The materials needed for the additives are partly renewable, partly obtained from fossil oils. The cardboard covering is produced from a minimum of 90% recycled cellulose.

Apart from dust, the production of gypsum boards has no particular problems. However, there can be problematic chemical additives, such as the retarding agent diethyl triamine, which is a strong respiratory irritant. Methyl chloride, which is a nerve gas, is employed in the production of silicone. Once in the building, however, gypsum products cause no problems.

Gypsum products are less well-suited for re-use, but can be recycled by using 5 to 15% waste gypsum in new products. The gypsum industry is very centralized, which often makes recycling an uneconomic proposition. There is a chance of sulphur pollution from demolition and building waste because of microbiological breakdown.

14.3.3 Fossil meal products

Fossil meal is a product of sedimentary earth which can be used as fill or aggregate in cast cement blocks or insulating mortars. Fossil meal products have good thermal properties and a high moisture absorption rate, making them best suited for insulation of high temperature equipment such as kilns, kettles, hot water tanks, baking ovens and high temperature equipment in industry. They can also be used in walls between rooms as a filler. Having a powder-like consistency, they must be placed between paper sheets so as not to leak out into the room.

Fossil meal mortars are made by mixing fossil meal with limes or cements. Addition of plant fibres is possible up to 30% by weight. Water is added and the ingredients are well mixed together. The mortar is then ready for use on hot water pipes, for example, preferably in several layers, each 1–2 cm thick. A canvas is bound over the last layer, which can be painted or rendered with lime.

Blocks of fossil meal can be made using cement as a binder. It can also be used as an insulating aggregate in brick products.

Fossil meal contains large amounts of silicon dioxide and can be superficially considered dangerous as it can cause silicosis. However, in fossil meal this substance is not crystalline silicium oxides as in quartz, but an amorphous version that is completely harmless. Fossil meal is in relatively widespread use, and causes considerable blemishes on the countryside when extracted. The waste phase does not cause any problems. Unmixed parts can be re-used or can even be left in the natural environment, covered with earth.

14.3.4 Perlite and pumice products

Perlite is a natural glass of volcanic origin mined by open cast methods in parts of the world such as Iceland, Greece, Hungary and the Czech Republic. It is pulverized and expanded in rotating kilns at about 900–1200 °C, which increases its volume between five and twenty times. Expanded perlite was first produced in the USA in 1953. It has the consistency of small popcorn and is used as an aggregate in mortars, plasters and lightweight concrete blocks. It is also used as loose fill for the thermal insulation of buildings, insulating refrigerating rooms and high temperature insulation. It has soundproofing properties similar to those of rockwool.

Using perlite as an aggregate in plasters and mortars provides a substantial increase in the thermal insulation of a wall. For example, 15 mm perlite plaster is the equivalent of a whole brick wall thickness or 240 mm concrete. Perlite can also be added to earth constructions to improve insulation properties.

Because perlite absorbs some moisture it runs the risk of a reduced insulation value; or an increased settling problem within a conventional wall construction when the material is used as a loose fill. To avoid this, a moisture repellent is often added to the mix before it is poured into the wall. This can be a natural resin. However, the most common method is to mix in silicone (less than 0.5% by weight) and heat it to 400 °C, *Hyperlite*. Bitumen can also be used.

When perlite is exposed to even higher temperatures naturally, it expands and becomes a porous and monolithic rock called pumice. The pores in this stone are not connected, so the material does not absorb any water. Building blocks of crushed pumice in cement have almost the same properties as when light expanded clay aggregate is used.

Perlite reserves are large. Pumice occurs naturally and in large quantities in Iceland. Both are extracted by open cast mining with the environmental disturbance which that entails. A pollution risk of perlite is that it can cause irritation by exposure to its dust. The use of bitumen and silicone additives brings in the issue of oil extraction and refining. This can also include exposure to toxic substances in the production workplace. Pure and silicone-treated perlite has no side effects once installed in a building. Depending on how the bituminous products are incorporated, small emissions of aromatic hydrocarbons may occur.

As a waste product, bituminous perlite must be disposed of at special depots. Pure perlite is inert. The siliconized material is also considered inert. Re-use is possible by vacuuming the loose material out of the structure.

14.3.5 Vermiculite products

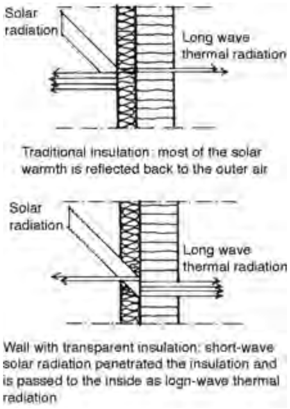
Vermiculite is formed through the disintegration of mica, which liberates lime and takes up water. When vermiculite is heated to 800–1100 °C, it divides into thin strips. These release water, curl up like snakes and swell to become a light porous mass which can be used as an independent loose insulation or as an aggregate in a lightweight concrete, e.g. in the proportions 6:1 vermiculite to Portland cement.

Other mineral binders can be used. Prefabricated slabs are made in varying thicknesses, from 15 to 100 mm.

Vermiculite easily absorbs large amounts of moisture, and substantially more than untreated perlite. It is therefore particularly useful for insulation of high temperature equipment. As normal wall insulation, it has a tendency to settle a great deal. This can be solved by applying compression up to 50%, using a coarser form of the material.

The environmental picture is approximately the same as for perlite, except for a few extraction sites where there have been shown to be significant amounts of asbestos (Curwell *et al.*, 2002).

14.3.6 Silica aerogel



14.8

Transparent thermal insulation.

By adding hydrochloric acid to a solution of potassium silicate (waterglass), silicic acid is formed in a jelly type mass, 'aerogel'. It is used as transparent thermal insulation, usually between two sheets of glass. The sun's radiant energy penetrates the gel, while it prevents the loss of heat through convection and loss of long-wave radiation (Figure 14.8).

A transparent layer of insulation on the south wall of a brick building can provide much of the heat it requires. Heavy brickwork will even out the temperature and prevent overheating or too much cooling.

Silica aerogel is at present not in general use, and has disadvantages: it does not tolerate water and has a tendency to crumble. But it has few negative consequences in relation to the environment or resource extraction.

14.3.7 Foamglass

Foamglass is usually produced by adding carbon to melted glass and heating it to 700–800 °C until it starts bubbling. A small amount (0.4%) of manganese dioxide is also added.

Foamglass is usually made in the form of slabs. These are gas and watertight with high thermal insulation properties, and they are mainly used as insulation underneath ground floors and in flat roofs, usually cemented together with a bituminous mass. The basic material is most often new glass, but up to 38% of recycled glass can be added.

A rougher loose-fill product of 95% recycled glass consists of expanded glass granules (Figure 14.9). The product absorbs little moisture and is well-suited to damp conditions. It is therefore much used as a thermal insulation and capillary break in slab-on-grade foundations. It is also used as a lightweight ingredient in mortars and concrete blocks.

Products based on new glass require a lot of energy and cause environmental emissions (see Chapter 6). Products manufactured from recycled glass are environmentally better, despite the still high temperatures needed when re-melting the glass.

These products present no problems within buildings. One possible exception is the use of bitumen as a jointing material. Glass products have no moisture regulating properties. Extensive use of them in a building can lead to an indoor climate with rapid air moisture changes and, in certain cases, the possibility of high levels of humidity in adjacent materials.

14.9

Expanded granules of recycled glass used as thermal insulation and capillary breaking layer in foundation. Gaia Tjøme, 2005.

Cleaned slabs and granules can be re-used in buildings. There is no way of recycling foamglass by re-melting. But it is practically inert and can be crushed and used as an insulating layer in road building. Components containing bitumen must be disposed of at special tips.

14.3.8 Mineral wool

Mineral wool has excellent thermal insulation properties. In addition, it is a reasonably good acoustic insulator. It is normally produced in mats, but occasionally also as loose fill.

Glasswool is made from quartz sand, soda, dolomite, lime and up to 65% recycled glass. Up to 9% borax is added to reduce the energy required in production. The mass is melted and drawn out into thin fibres in a powerful oil burner. Glue is then added to the loose wool and heated to form sheets or matting in a kiln. Phenol-formaldehyde glue (PF) is commonly used in a proportion of about 5.5% of the product's weight. To give a high thermal insulation value the diameter of the fibre should be as small as possible. The usual size is about 5 μm.

Rockwool is produced in approximately the same way as glasswool, starting with a mixture of coke, diabase and limestone. Basalt and olivine can also be used. The quantity of phenol-formaldehyde glue is lower, about 2% by weight. The diameter of the fibres varies from 1 to 10 μm.

Both types of mineral wool have silicone or aliphatic mineral oils added up to 1% by weight as water repellents and dust bonding agents.

When used as insulation, both glasswool and rockwool need a tight vapour membrane of aluminium foil or plastic sheeting, partly to avoid dust entering the interior and partly because the materials cannot regulate moisture well. Research has shown that the use of rockwool and, to a certain extent, glasswool can increase mould growth and damage caused by damp on the timber framework, unlike the more hygroscopic insulating materials such as cellulose fibre (Paajanen *et al.*, 1994).

Man made mineral fibres(MMMF) such as in rockwool and glasswool are suspected of being carcinogenic. The risk relates both to the physical thickness and length of the fibres as well as to their chemical composition. In recent years many manufacturers have improved their products to eliminate this risk. However, the fibres are still strong irritants both to skin and respiratory organs and can lead to chronic bronchitis. Workers both in the factories and on building sites are often exposed. Acoustic panels with mineral wool are the most common source of mineral wool fibres in the indoor climate (Bakke, 1992).

It has been shown that humidity in mineral wool can lead to the emission of vapours that can later enter the building. The problem is more acute when the wall becomes warm; for example, through solar radiation. The gases released are aromatic and aliphatic hydrocarbons. Formaldehyde, which is carcinogenic, can also be emitted from glasswool products. All of these gases irritate the ears, nose and throat (Gustafsson, 1990). Additives in mineral wool that contain nitrogen are very susceptible to mould. The amount of mould in an infected material can be 1000 to 50 000 times the amount in uninfected material (Bakke, 1992).

Raw materials are abundant for the main constituents of glasswool and rockwool. The production of glasswool occurs in relatively closed processes. The emissions from production are little and limited to formaldehyde and dust in addition to energy pollution. Phenol, ammonia, hydrogen cyanide, formaldehyde and dust are released during the production of rockwool, and large amounts of waste are produced. Phenol can leach out of rockwool waste. Unpolluted waste can be compressed and recycled for the manufacture of new mineral wool, although the industry is so centralized that this form of recycling is economically unrealistic.

14.3.9 Montmorillonite

Montmorillonite occurs mainly in bentonite. The minerals in montmorillonite not only absorb water on the surface, but also within its mineral structure. It has a capacity to absorb large amounts of water and swells up to twenty times in volume. This absorption occurs quickly, and when the surroundings dry out again the clay releases its moisture. It is, therefore, useful as an absorbent waterproof membrane on foundation walls made of brick and concrete. Bentonite clay can be purchased in panel form, packed between two sheets of corrugated cardboard: the clay is approximately 0.5 cm thick and the cardboard gradually rots away intentionally. The panels should be under a certain pressure, which can be achieved by a compressed layer of earth of at least 0.4 m.

There is an abundance of montmorillonite clay, but in very few places, so high levels of transport energy are needed. Like all mined substances, large mines cause local environmental damage. Apart from this the environmental problems of the product are of no consequence.

14.4 FIRED CLAY MATERIALS

Basic info is found in Chapter 8.

Fired clay in the form of bricks is mainly a structural material and has high thermal conductivity. However, it is possible to add substances to the clay that burn out during the firing and leave air pockets in the structure. The lighter product that results can be found in slab or block form.

Clay can also be expanded to light expanded clay pellets for use as loose fill or cast with cement to form blocks or slabs. By exposing light expanded clay to even higher temperatures, the light, airy granules cohere into a solid mass that can be used to form blocks known as Zytan. This type of block is not in production due to high energy use in manufacture.

All fired clay products are chemically inactive. In the indoor climate there are no problems with these products.

Certain types of brick products are good moisture regulators, the more developed the microporous structure, the better. Low-fired

Table 14.6 *Climatizing qualities of fired clay products*

Material	*Areas of use*
Vitrified and well-fired bricks[1]	Thermal buffering, sound insulation
Low and medium fired bricks[1]	Thermal buffering, moisture buffering, sound insulation
Bricks with high lime content (15–20% lime)[1]	Thermal buffering, moisture buffering, sound insulation
Porous bricks	Thermal insulation, thermal buffering, moisture buffering, sound insulation
Expanded clay pellets, loose	Thermal insulation, capillary barrier
Zytan block	Thermal insulation, sound insulation

[1] Discussed in Chapter 13, Structural materials.

brick and brick with a high proportion of lime give the best results (Figures 14.10 and 14.11). Because of the large amount of energy needed in manufacture, all fired clay products should be recycled, preferably by re-use in their original undamaged form. Coloured and glazed clay products may contain heavy metal pigments, and as a result can cause problems when they are finally disposed of.

Lightweight bricks and blocks are fired at temperatures of 1000 °C or more. The organic ingredients (sawdust, pieces of cork, etc.) are burnt away to leave an internal structure with isolated air holes. In one particular product, granules of polystyrene are used. During the firing the polystyrene granules vaporize as water, carbon dioxide and

14.10

Porous brick with lime rendering balancing humidity in a bathroom. Hydraulic lime mortar is used to improve the potential for re-use of bricks. Gaia Lista, 1996.

14.11

Exterior of bathroom shown in Figure 14.10. Both walls and floor consist of mineral materials only, to prevent moisture damage. Perlite is used as thermal insulation. Gaia Lista, 1996.

styrene, the latter being regarded as a serious toxin. The completed product is probably free of polystyrene.

Insulating aggregate such as fossil meal can be added and once fired the blocks have a relatively high thermal insulation value.

FIRED CLAY PRODUCTS WITH FOSSIL MEAL AS THERMAL INSULATION

One part clay is mixed with 15 parts fossil meal into a homogeneous mass. It is also possible to add 25% sawdust or pieces of cork before the mass is pressed into forms and fired at approx 1000 °C. Products are primarily loadbearing blocks and slabs. Blocks with sawdust or cork pieces are primarily used for insulation.

Light expanded clay pellets can be used as loose fill or cast with cement into blocks or other structural units, as well as in insulating earth blocks. They have a fairly good thermal insulation value. Loose expanded clay pellets can be used under the slab of a building as a capillary break.

Light expanded clay products have good structural properties, but they are poor moisture regulators because the pore structure is closed.

Blocks and prefabricated units are well suited for dismantling and re-use as long as they were originally fixed together with weak mortars or mechanical jointing. Loose expanded clay can also be re-used if they have been protected from roots, sand and earth. All expanded clay products are inert and can be recycled for use as insulating aggregate under roads, etc.

14.5 EARTH AND SAND AS CLIMATIC MATERIALS

Basic info is found in Chapter 8.

Plain earth does not have good thermal insulating properties but, as with most materials, a thick enough layer can provide what is needed. In the animal world it is common for rodents or other wild animals to live in shelters dug down in the earth. Humans have also used this to their advantage, and there are examples of underground buildings in most cultures, including underground villages in China, Turkey, Tunisia and Mexico (Figure 14.12).

UNDERGROUND BUILDINGS

There are many variants, both ancient and modern, of earth sheltered or fully underground buildings. An underground building can be defined as a house having its roof and at least two walls covered by layers of earth more than 50 cm deep. The insulation value of earth is about one-twenty-fifth of the value of mineral wool, so if the roof is thinner than 2–3 m, extra insulation is needed. By planting trees or bushes on the roof, heat loss is reduced. The building should preferably be on a south-facing slope to take advantage of solar radiation and the floor must be higher than the water table. The loading on the roof can be more than ten times that of a normal building and the pressure on the walls slightly greater than on a normal basement wall. It is important

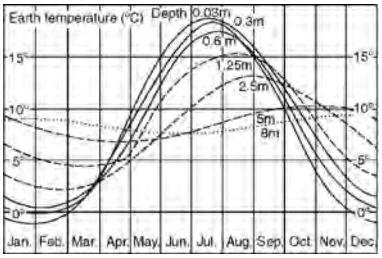
14.12

A traditional subterranean dwelling in atrium style in North-western China. These houses have proved to combine low energy use with a high quality indoor climate (Chen et al. 1997).
Source: Anne Sigrid Nordby.

to have good drainage from the roof, which should also be laid on a well-drained material with a high friction coefficient.

These days, houses are generally built above-ground. There are probably cultural reasons for this move to the surface of the Earth, because, practically speaking, nothing is as sheltered as an earth-sheltered house. In the USA, over 600 underground buildings were erected between 1978 and 1980, including homes, libraries, schools and office buildings. This happened even though the cost of an underground building has been calculated at about 10–20% more than that of a conventional building (Winquist, 1980).

One main aim of an underground house is to save energy, and it is symptomatic that the sudden rise in popularity came after the energy crisis of the early seventies, only to fall again once oil prices began to fall. Temperatures at a certain depth underground are stable over the year: they are warmer in winter and less cold in



14.13

The temperature at different depths of the Earth throughout the year in southern Scandinavia.

Source: Låg, 1979.

summer (Figure 14.13). At 20 cm below the surface, the variations in temperature over a 24 hour period are hardly noticeable. This means smaller temperature changes in the fabric of the building and thereby fewer maintenance problems and a longer life span. These houses cannot, of course, be built where there is radon in the ground.

Naturally, traditions of underground building are most prevalent in regions where the soil or rock is easy to excavate. The American experience is that underground houses are best suited to sunny climates with cold nights. In such locations energy consumption is reduced by 20–80%.

Structures built in on the surface of the earth also have interesting climatic aspects, particularly with respect to temperature equalization and moisture buffering.

Only about the outer 2 cm of the material will be active as a humidity regulator during a 24 hour cycle, but the moisture buffer value is probably better than for both timber and aerated concrete (Minke, 2006). In Northern Europe there are indoor swimming pools and moisture-sensitive libraries built with clay as the main material. Also, a whole series of earth-based plasters has been developed for concrete and hard fired brick in order to reach a more stable humidity within the building (Figure 14.14).

To achieve reasonable thermal insulation a porous substance can be added. This can be expanded perlite, crushed pumice, foamed glass granules or plant matter such as sawdust, wood shavings, cork or straw, see later sections in this chapter. Earth is also wind-proof when compressed.

Water will not usually penetrate a horizontal layer of earth more than 50 cm deep. Thick traditional earth roofs found in Iceland are therefore relatively safe from leakage. Earth containing a large quantity of clay is waterproof, even in thinner layers. The optimal clay is bentonite (see 'Montmorillonite' page 262), which is waterproof at only 0.5 cm thickness.

TWO RECIPES FOR WATERTIGHT LAYERS OF EARTH

In *The Art of Building* Broch suggests the following recipe for waterproofing a brick and stone vault (Broch, 1848): first a 3-inch thick layer of coarse sand on the vault, then a layer of finer sand, then 6 inches of clay mixed with soil and finally a layer of turf. We have to assume that he was dealing with mausoleums and fortresses.

The 'Podel' mixture, launched by James Brindley in 1764, was a method for damming water. The method is most interesting for external spaces: one part soil and two parts coarse sand are mixed, then stamped together or made wet until they do not let through any more water. The minimum thickness of the layer is 70–90 cm.

Clay as an infill between the joists in a floor space has sound insulating, moisture regulating and, to a certain extent thermally insulating properties. It can also assist the energy balance through its high thermal storage capacity.

14.14
Layer of compressed earth balancing air moisture and temperature in a hospital in Feldkirch, Austria. Architect: Martin Rauch; Photo: Alice Reite.

FILLING WITH CLAY BETWEEN JOISTS

The clay is mixed with chopped straw, sawdust or similar material, and water is added, so that the mass assumes the consistency of porridge. This is used for the lowest layer, and should hinder leakage into the rooms below. When this has dried and stiffened, the cracks that have formed are filled by pouring a thin clay gruel over. The rest of the space is filled with dry clay up to the top of the joists.

Pure sand is also often used as sound insulation in the floor structure. It is heavy and is effective since it fills up all small spaces around the joists.

All climatic earth materials are favourable from an ecological point of view. This includes all phases, from extraction as raw material to final disintegration. In the indoor climate, earth is healthy and is not a problem as long as it is not exposed to continuous damp conditions.

14.6 BITUMEN BASED MATERIALS

Basic info is found in Chapter 9.

Bituminous products have good waterproofing qualities and are often used for waterproofing membranes in both the exterior and interior of a building, as well as in roof coverings. The first known building-use of bitumen can be traced back about 5000 years to the Indus valley, where it was used to make a temple pool watertight. This fatty and water-repelling material is also often mixed into other building materials that are exposed to moisture such as perlite insulation and wood fibre wind barriers. Coal tar was once used instead of bitumen – such products are no longer in use.

For use as a waterproofing membrane, it is common practice to first oxidize the bitumen mass by blowing air into it. The material is then

14.15

Cabins partly buried in a sensitive area along the south coast of Norway. The materials and structures have been chosen with respect to the local climate and properties in earth and ground water. The aim has been to reduce the physical and chemical traces of the buildings to a minimum when they eventually fall to ruin. Gaia Lista, 1997.

heated and applied directly onto the surface, e.g. a foundation wall. Solvents can be added to give a more workable consistency. A filler such as crushed limestone or sand can be used. Waterproof sheeting is produced by coating a base product of polyester, fibreglass, rag fibre or paper with bitumen. Small granules of ground stone can be added to give a more resistant surface. Bituminous mastic for making joints watertight consists of a solution or emulsion of bitumen with fine stone powder or synthetic rubber. The mixture contains high levels of solvents.

Bituminous products do not have a long lifespan if they are exposed to a combination of sunlight, large variations in temperature and a lot of damp. They can also be attacked by acids found in soil. When protected from these conditions they can be very durable.

Bitumen is derived from fossil oils, in particular the heavy fractions of crude oil. The production of bitumen-based materials is therefore unsustainable, intensive in its use of energy, and also causes pollution – however, on a somewhat lesser scale than that of oil-based plastic products.

Heating bitumen on a building site emits dangerous fumes: polycyclic aromatic hydrocarbons (PAH) amongst others, though the amount of PAH in bitumen is considerably lower than that in coal tar. Some of the products contain organic solvents (see Table 9.4), which are also easily emitted even in a cold state.

If bitumen products are exposed to heat or sunlight, fumes can be released into a building. Bitumen products cannot usually be re-used or material recycled. For enhanced recycling of adjoining components in concrete or timber, loose membranes are preferable to membranes poured in situ. Both bitumen and coal tar contain substances that are the initial stages of dioxins, which can seep out; waste products should therefore be carefully disposed of (Strunge *et al.*, 1990).

14.7 PLASTIC MATERIALS

Basic info is found in Chapter 9.

Many plastics have high thermal insulation properties when foamed and good water and vapour-proofing properties when used as paint, sheeting, sealing strips and mastics.

Sheets and membranes. Several plastics are used for sheeting and membranes. Most important are polypropylene, polyethylene, polyvinyl chloride and synthetic rubbers.

Vapour retarders are often made of spun high-density fibres of polyethylene or polypropylene. These products are also often used as air and wind barriers. Polyethylene is the most frequently used plastic sheeting for *vapour barriers*, either alone or as coating on paper sheeting. Polyvinyl chloride sheeting is not as vapour proof as polyethylene, but it is still used for this purpose when higher strength is required.

Polyvinyl chloride and the synthetic rubbers polyisobutylene (PIB) and styrene butadiene (SBR) are much used as *waterproofing membranes* in bathroom floors and walls.

External moisture proofing on foundations (geomembranes) are often done with profiled sheeting made of polyethylene or polypropylene, usually with carbon as ultraviolet stabilizer. In some products polyester fibres are used as reinforcement. Polyvinyl chloride and synthetic rubbers are much used as roofing membranes, especially on flat or nearly flat roofs.

Flashings and gutters. The most common plastic for use in flashing and gutters is polyvinyl chloride. Products are often coloured and stabilized with cadmium or organic tin compounds.

Mastics and sealants. Apart from linseed oil based putty, most mastics available on the market today are plastic or bitumen based. A mastic has to fulfil conditions of constant elasticity and high durability. The plastics commonly used are polysulphide, silicone, polyurethane and various acrylic substances. These compositions are complex, the binders being mixed with fillers, organic solvents, drying agents, softeners and biocides. Some products also have pigments and fibres added, the latter usually fibreglass. Pure silicone is easy prey for mould in damp situations, and therefore often has isothiazolinones, carbendazim or organic tin compounds added, about 0.05% by weight. Organic arsenic compounds are also used as a biocide in some products. Polyurethane mastics contain 10–60% phthalates. Other products can contain chloroparaffins as softeners. Mastics of polysulphide, polyurethane and polyacrylates can contain brominated or chlorinated hydrocarbons as fire retardants. Up to the end of the 1980s highly toxic polychlorinated biphenyls (PCBs) were an important part of mastics for sealing between modules in prefabricated buildings, as well as in sealants between glass layers in insulating windows.

Sealing strips are used mainly between the sheets of glass in windows and in window and door reveals. Important plastics used include polyurethane, polyamide, polyvinyl chloride, ethylene-propylene rubber (EPDM), choloprene rubber (CR) and silicone. The products include different additives such as fire retardants, stabilizers and pigments.

Thermal insulation. Various insulation materials are produced from foamed polystyrene (EPS, XPS, MEPS) and polyurethane. Polyisocyanurate and polyicynene are recent alternatives with similarities to polyurethane. Foamed polyvinyl chloride, polyethylene and phenolic products are also used, but to a lesser extent. A fairly new product group is based on the recycling of plastic bottles made of polyethylene which are shred, and are produced as matting. The other materials are foamed up using hydrofluorocarbons, pentane or carbon dioxide as foaming agents. As fire retardents brominated and chlorinated hydrocarbons are often used, the largest portions in polyurethane products.

14.7.1 Environmental aspects

Almost all commercial plastics are based on fossil carbon resources, mainly oil and gas. The resource base of plastics is thus very limited, energy consuming, heavily polluting and a major source of climate emissions. Refining plastics requires a great deal of energy compared to other materials. In all phases from production to use in the indoor climate and as waste, the majority of plastic products can cause considerable health risks and pollution. This includes a broad spectre of environmental toxins in addition to the greenhouse gas carbon dioxide (see Chapter 9).

Plastic sheeting plays a very important role in water and vapour-proofing of conventional buildings. Durability is therefore a decisive factor. According to existing documentation it is unlikely that plastic products have these qualities to the desired extent. In terms of pollution, products made of polyethylene and polypropylene are unproblematic in the user phase. Sheeting and membranes made of polyvinyl chloride can contain softeners (phthalates) and other volatile additives that can cause problems if exposed in the indoor air. In waterproofing membranes for bathrooms, residues of bisphenol A and phosphates of lead have been documented. Products of polyvinyl chloride also often contain the potent heavy metals cadmium or lead as a stabilizer against ultraviolet radiation. Heavy metals are also commonly used in flashings and gutters made of polyvinyl chloride.

Mastics must be applied when still soft. During the hardening process, the indoor climate can be affected by emissions of aromatic, aliphatic and chlorinated hydrocarbons. At the Royal Theatre in Copenhagen, an unpleasant smell (best described as garlic or rotten eggs) occurred after the use of a mastic, which was responsible for the release of sulphur compounds on oxidation with the air (Gustafsson, 1990). There have also been many cases of serious mould growth on polymer mastics in bathrooms. Mastics break down when exposed to weather and wind, becoming powdery. They then fall into or out of the joint and represent a toxic risk both inside the building and for the surrounding soil. This decay progresses much more quickly than was assumed during the 1960s when building methods with precast concrete elements began – these days, a large number of buildings have considerable problems and high maintenance costs as a result. The limited durability of mastics is in sharp contrast to the vital functions they are put to perform: air and wind-proofing and, above all, waterproofing. Mastic joints in construction are also often invisible for later inspection. Their use should be reduced to a minimum.

Sealing strips of plastic are already hardened by the manufacturer and are a lower pollution risk in the indoor environment. However, their durability is much shorter than the products they are built to protect, and they can be difficult to replace after a few years.

Thermal insulation made of polystyrene is always delivered as a ready made product. The same is the case for some types of polyurethane-based insulation, though it is most often blown into buildings on site, being used in particular for filling around windows and doors. Urea formaldehyde foam is always sprayed in on site. The latter emits fumes during the hardening phase, particularly formaldehyde. Depending upon how the materials are installed, ready made products of polystyrene can emit monomers of styrene. From foamed polyurethane there can be emissions of unreacted isocyanates, which are highly toxic even in small concentrations, as well as amines. Emissions of brominated hydrocarbons have also been registered from polyurethane products. Chlorofluorocarbons and hydrochlorofluorocarbons can be emitted during the whole material lifecycle where these are used as foaming agents. This leakage also reduces the insulating properties considerably.

Plastics-based insulation materials have no moisture buffering capacity.

The re-use of plastics-based climatic products is not particularly appropriate because of their short lifespan. Even material recycling of climatic plastic products is not very practicable, as most of them are fixed to other materials. An exception is products consisting of pure polyethylene, polypropylene and polyvinyl chloride that can often be down-cycled to manufacture a range of more or less useful low quality plastic products.

Most plastics can be transformed to energy by combustion in special furnaces with smoke cleaning systems. One should remember that since these are originally oil products, there are corresponding carbon dioxide emissions. Ashes from the furnaces, and plastic waste that is not recycled, must be disposed of safely to prevent seepage into the ground water or soil. Quite a few plastics, especially where there are additives, pigments, softeners, etc. have to be treated as special waste. Once on the refuse tip most plastic waste is not naturally degraded.

14.8 TIMBER MATERIALS

Basic info is found in Chapter 10.

Timber has many good climatic properties both in its solid state and in a shredded or particle form. Log walls have covered all the climatic functions in Scandinavian dwellings for hundreds of years; timber is wind-proof, it is a good regulator of moisture, and it has a reasonable insulation value. However, even thick log walls do not quite fulfil present insulation standards, which can only be reached by adding extra insulation on the outside. A good insulation value can also be achieved by sufficiently thick massive wood elements (see Chapter 14). This is particularly so where the timber is joined with dowels rather than glue and small air spaces between the boards add insulation value; the boards can be grooved to increase this effect.

When timber is reduced to smaller dimensions, it will gain even better qualities as thermal insulation. Sawdust, shavings and woodwool are available from all timbers. These can be used directly as compressed loose fill. In Sweden, Finland and inland Norway this was the most widespread form of insulation in framed building up to the 1950s. These materials are also made into sheets, slabs and building blocks by adding cement or glue. Woodwool cement boards are much used as acoustic ceilings and baffles. Sawdust, wood shavings and chips can also be used as a lightweight aggregate in earth construction. More finely shredded material, *defibrated wood fibres*, provides a basis for highly insulating products, either as loose fill or as glued matting and boards. In some board products the wood particles themselves provide the

Table 14.7 *Acclimatizing qualities of wood products*

Materials	*Composition*	*Areas of use*
Massive wood constructions[1]	Untreated timber	Thermal buffering, moisture buffering, sound insulation, thermal insulation[3]
Timber panelling and flooring[2]	Untreated timber	Moisture buffering
Cork, loose fill and boards	Granules of cork oak. Boards are glued with bitumen, gelatine etc.	Thermal insulation, moisture buffering, sound insulation
Sawdust and wood shavings, loose fill	Wood particles, possibly with whey, soda etc. added	Thermal insulation, moisture buffering, sound insulation
Woodwool cement	Woodwool, sodium waterglass, cement, water	Thermal insulation, moisture buffering, sound insulation
Wood fibre, loose fill	Defibrated wood fibre, ammoniumphosphates, possibly borates	Thermal insulation, moisture buffering, sound insulation
Wood fibre matting	Defibrated wood fibre, glued with starch or polyolefins (melted), additives[4]	Thermal insulation, moisture buffering, sound insulation
Porous wood fibre boards	Defibrated wood fibre, glued with lignin, polyurethane bitumen etc., additives[4]	Thermal insulation, moisture buffering, sound insulation, wind barriers
Hard wood fibre boards[2]	Defibrated wood fibre, glued with lignin, phenol formaldehyde, polyurethane etc, additives[4]	Vapour retarders, air barriers
Cellulose fibre, loose fill	Recycled cellulose fibre, borax, boric acid	Thermal insulation, moisture buffering, sound insulation
Cellulose fibre, matting	Recycled or virgin cellulose fibre, glued with polyolefines or polyesters (melted), additives[4]	Thermal insulation, moisture buffering, sound insulation
Cellulose building papers and sheets	Recycled or virgin cellulose, sheets are laminated with polyvinyl acetate etc., possible additives of latex, bitumen etc.	Vapour retarders, air barriers, wind barriers

[1] Discussed in Chapter 13, Structural materials.
[2] Discussed in Chapter 15, Surface materials.
[3] Depending on construction method.
[4] See page 280.

glue, lignin, during the process when the boards are manufactured under heat and pressure. Defibrated wood fibres are also used as a basis for cellulose products, see page 289.

The bark of some trees can also be of use as a climatic material. Bark from cork oak provides high quality thermal insulation. Bark from birch has been one of the most common waterproofing materials throughout history, especially as an underlay for roofs covered with turf.

Extracts from both coniferous and deciduous trees can also be used for waterproofing and impregnation.

Sustainable forestry and replanting schemes ensure that timber resources are renewable. Many of the products are even based on waste such as sawdust and wood shavings. However, some of the glues, flame retardants and fungicides used have a doubtful environmental profile.

The energy use in timber production processes varies a lot from product to product, but it is generally much lower than similar products in other materials. Exceptions include wood fibreboards that require high process temperatures, and woodwool slabs which comprise a high proportion of cement.

Pollution arising in the different levels of production, usage and waste is relatively small. In this picture, the ability to store carbon should also be accounted for.

Timber-based climatic materials can generally be considered as durable and stable. If treated with care, the denser board, block and slab products can be re-used. This is, in principle, also the case for loose fills that can be sucked out and used in new constructions. Pure wood can be recycled as raw material for the production of particle boards and even for certain wood fibre products.

All timber products can be recycled for energy. This potential is somewhat reduced in the case of products containing cement or where fire retardants have been added. Glued products and products treated with fungicides, flame retardants and similar, often require combustion in furnaces having high quality flue gas cleaning. This is unnecessary for pure timber products. These can also be composted, as long as the process is controlled to avoid potential eutrophicating effluents.

14.8.1 Sawdust and wood shavings

Loose fill of sawdust and wood shavings is timber in a very pure form, and can be used as thermal insulation in walls, floors and ceilings (Table 14.8). Sawdust and wood shavings are fine-particled, hygroscopic materials that take up moisture and release it into the air in

Table 14.8 *Thermal properties of sawdust and wood shavings*

Material	*Weight (kg/m^3)*	*Specific thermal conductivity [W/m K]*
Sawdust		
Compressed	120	0.071
Well compressed	200	0.081
Mixed with sand (2:1)	750	0.100
Wood shavings		
Slightly compressed	80	0.120
Compressed	130	0.080
Well compressed	150	0.070
Highly compressed	180	0.060
Rinsed and slightly compressed	80	0.045
Rinsed and compressed	125	0.055

(Source: Granum, 1951; Baufritz, 2007)

14.16

Wood shavings as thermal insulation in industrialized building. Carrying out the insulation work at the factory secures complete filling of the building elements.

Source: Baufritz.

the same way as timber, but at a slightly higher rate. They also have the same resistance to fungus and insects as timber.

Commercial products based on wood shavings have had a certain success in the central European market. There are two main versions, differing in the type of fire and insect protection used. Most common is a product where whey and soda are added for these two purposes, respectively; the other adds up to 25% liquid cement for both purposes.

Production of these materials requires little energy – except where cement is added – and they are benign in the finished building. Experimental buildings investigated by Professor Bugge at the Norwegian Institute of Technology demonstrated that after 30 years the sawdust was in perfect condition, with no sign of deterioration. The buildings stood on the very damp west coast of Norway (Granum, 1951). Loose fill can fairly easily be taken out and re-used.

PRODUCTION OF RINSED WOOD SHAVINGS

The shavings are normally waste products at sawmills and other wood industries, and are prepared as follows:

1. Rinsing. To ensure a good insulation value, fine particles and dust must be removed by sieving.
2. Drying to less than 20% water content, often in a rotating drum.
3. Addition of fire retardants and fungicides.
4. Packaging in large sacks with only light compression.

14.17

Prefebricated house insulated with wood shavings.

Source: Baufritz.

14.8.2 Bark

Cork oak is found in warm climates and is principally grown and used in southern Europe, in Portugal, Spain and North Africa. Cork can be harvested as a regular crop every 10–12 years. This special kind of bark may have evolved to withstand the frequent forest fires that occur around the Mediterranean. The trees are ripe for stripping after 25 years and can then be stripped every 8 to 15 years. The material is used as thin boarding or crumbled for loose thermal insulation. It has high compressive strength and is therefore often used on flat roofs. It is also quite resistant to fungus.

Cork is composed of dead cell combinations of cork cambium and resins. It is usual to expand the cork to increase its thermal insulation value. In loose form, cork can be used for fillings in walls and as lightweight aggregate in concretes and earth constructions. Boards can be pressed at a temperature of 250–300 °C, thereby releasing the cork's own glue which eventually binds the board together. This process can be stimulated by adding laccase (Lund, 2003). Today, however, it is usual to bind the boards with bituminous material, gelatine or other glues in a cold process.

Many of the cork forests are now dwindling.

Birch bark. The bark of birch trees has traditionally been widely used as a waterproof membrane under turf roofs. It then has to be kept permanently damp to prevent it cracking.

Pieces of bark are taken from large birches, conveniently known as roof birches. A roof has between three and twenty layers of bark, depending upon the required durability. The bark is laid on the roof in overlapping fashion like any other waterproofing material. It is very resistant to rot and can be used as waterproofing also in other potentially damp areas, e.g. foundation walls. During the restoration of the Church of St Katarina in Stockholm in the early 1990s, 300-year-old birch bark was found at the end of inbuilt beams. They were exceptionally well preserved. The same method was therefore used in the restoration. In 1948, the Danish engineer Axel Jörgensen wrote: ‘Building traders should set up an import of birch bark from Sweden or Finland, so that we could once again use this excellent protective medium’ (Jörgensen, 1948).

Birch bark has also been used as insulation in walls, especially cavity walls, where its considerable resistance to rot and its high elasticity produces a durable solution.

Birch bark should be removed as carefully as possible, so as not to damage the tree’s vital layers. The resulting squares of 60 × 60 cm or more, depending on the diameter of the trunks, are piled up and weighted down with stones to reduce their curling. The tree can then continue to grow, though it may not produce more building quality bark. Bark is loosest during spring, and the best time to take the bark is after a thunderstorm (Høeg, 1974).

14.8.3 Woodwool cement

Woodwool cement is usually produced as boards in thicknesses of 2.5 to 15 cm, but can also be produced as structural blocks. Reinforcing the thickest boards with round wooden battens produces a material with good structural properties. Woodwool cement is also used as an ingredient in some sandwich boards, glued or heated together with layers of polystyrene, polyurethane, rockwool or foamglass.

Woodwool cement is resistant to rot. It has a weak alkaline content of about pH 8.5; mould needs a pH of 2.5–6 to develop. Woodwool can therefore be used as foundation wall insulation. The woodwool should be laid on the inside, because running water in the earth will wash away the cement in the long term. The sound absorption qualities, when it is not rendered, are very good, and the boards are suitable for use as acoustic cladding.

The product is a simple mixture of woodwool and cement. Natural acids in the wood shavings have to be rinsed out first, either by boiling or in a solution of sodium waterglass or calcium chloride. Alternatively, the shavings can be left in the open air to oxidize for about a year.

Woodwool cement consists of 45–65% cement by weight. The role of the cement is therefore quite decisive in an environmental evaluation, since cement implies high energy use and emissions of carbon dioxide, etc. in production. Woodwool cement products cannot be recycled as material or burned for energy recycling. Boards that are mechanically fixed can, in principle, be re-used whole. Waste is almost inert.

14.8.4 Defibrated wood fibre

Loose fill insulation in the form of defibrated wood fibre resembles the better known cellulose insulation, and has been on the market in Europe for some 20 years. It is primarily thermal insulation but at higher densities also useful as sound insulation.Defibrated wood fibre also forms the basis for all fibre based matting and board products.

Defibrated wood fibre is usually produced from conifers; wood wastes can also be used. Fire retardants are added, normally about 5% ammonium phosphate; for higher fire standards up to 10% borates can be used, which also have an anti-fungal effect. Aluminium phosphate can also be used as fungicide.

The loose fill is blown into the construction using one of two methods. It can be blown into the finished wall through holes, or else blown before the interior cladding is fixed. The latter probably ensures better filling. Minimum density should be 65 kg/m^3 to avoid settling with resultant uninsulated gaps at the top.

Energy use in production is low and additives used are relatively unproblematic, with the exception of the borates. Re-use should be quite easy, and these materials can also be combusted for energy recovery or composted.

14.18

Insulating with wood fibre matting.

Source: Homatherm.

14.8.5 Wood fibre matting

Wood fibre insulation mats are relatively new but are already widely used in central Europe (Figure 14.18). They are elastic, can be delivered in thicknesses from 40 to 200 mm, and in dimensions adapted to normal wall and floor beam framing. The weight is from 40 to 55 kg/m^3, but lighter versions of only 10 kg/m^3 are being developed.

The production takes place in a dry process (see page 280). The mats are most often fixated by melting in about 6–10% polyolefine fibres (thermal bonding), fibres based on maize starch are also used. Ammonium sulphate is almost always the fire retardant used. Fungicides are not added.

Resource and energy use is moderate; the alternative bonded with starch fibres would seem most eco-efficient, since polyolefines are produced from fossil oils. Indoor exposure is unproblematic. Re-use is possible if the mats have retained their elasticity, but there is as yet insufficient knowledge of how the glues will perform over time. These products can also be used for energy recovery or, with the maize variety, composted.

14.8.6 Porous wood fibre boards

Porous wood fibre boards can be divided into two main groups according to their weight; light boards of 110–170 kg/m^3 and heavy boards of 240–350 kg/m$^{3.}$ The former are produced in thicknesses from 20 to 200 mm, the heavy boards from 6 to 160 mm, sometimes as thinner sections laminated together. Compressive strength varies between 20 and 200 kN/m^2 for the light boards, and between 100 and 300 kN/m^2 for the heavy variety. Thus there is a broad range of possible applications.

The light boards have thermal insulation as a main function. The lightest types are quite elastic and can be pressed between joists or studs; otherwise the boards are mounted continuously on the outside of the construction so as to form a complete thermal layer without cold bridges.

The heavier boards have an equally important function as exterior cladding forming the stiffening (bracing) of the buildings. With water-repelling agents added they are often used as wind-proofing and as sub-roofing. Other types can be rendered on the outside surface. Yet another function of the denser types is as soundproofing under floor coverings.

The boards are produced by both dry and wet processes (see page 280). In the dry process, polyurethane glue (4%) or melted polyolefine fibres (10%) are used; in the wet process the natural lignin in the material forms the glue. Some recycled paper can be added in both cases.

Fire retardants such as ammonium sulphates or ammonium phosphates (about 3%) are commonly used. Aluminium sulphate speeds the action of the lignin in the wet process. By adding laccase even more lignin becomes available.

In the wet process, boards of over 30 mm thick must be laminated, and here polyvinyl acetate adhesive (PVAC) or waterglass adhesive is added. For exposed or humid conditions such as for exterior sheathing, water repellents are added, including bitumen, lateks, paraffin wax, colophony and waterglass, normally in tiny amounts, except for up to 20% in the case of bitumen.

Boards may be delivered with tongue and groove to ensure windproofing and no cold bridges. They are easy to cut and work with, and are fixed with staples or screws. As acoustic layer they are laid loose.

Energy consumption is considerable in the wet process, but additional glues are not needed; whereas the dry process normally demands high quantities of problematic glues. These include polyurethane adhesive and phenol-resorcinol-formaldehyde PRF. Bitumen may be used with both types and, being a fossil oil product, reduces the environmental advantages considerably. Stapled boards will be difficult to demount without breakage; re-use otherwise is possible, as well as energy recycling under condition that the synthetic glues and bitumen components can be taken care of.

PRODUCTION OF DEFIBRED WOOD MASS, MATS AND BOARDS

Defibrated wood mass can be produced from most kinds of conifers as well as wood wastes:

1. Shredding to chips of 10–40 mm.
2. Washing to remove impurities.
3. Steam treatment to soften the natural bonds in the wood material.
4. Grinding (defibration) to a pulp with fibres of about 1.5 mm.

The **wet process** is the classical process for the production of wood fibre boards where the lignin itself is released and bonds the product. Fresh wood must be used. Stiff boards up to 30 mm thick are produced, that can later be laminated to thicker elements. The process is as follows:

1. Mixing with water and spreading on to a rolling conveyor.
2. Squeezing to remove about half the water and pressing to thin sheets.
3. Rolling at around 200 °C to remove the remaining water and glueing of the sheets.
4. Cutting to standard board dimensions.

In the **dry process** glue is added as a binder; this means that old and deficient timber can also be used. Boards can be produced up to 200 mm thickness.

1. Drying of the mass at around 170 °C.
2. Mixing with glue and spreading into sheets on a conveyor.
3. Curing the sheets with warm humid air.
4. Cutting to standard mat and board dimensions.

Additives are mixed in at different stages depending on the type.

ADDITIVES IN PLANT-BASED INSULATION MATERIALS

Glues are necessary in the dry production processes, as well as in lamination to thicker elements. Polyurethane glue is much used, as well as melted fibres (thermal bonding) of polyolefine, polyester and maize starch, in quantities 4–18%. In the wet process 8–22% bitumen is often added for water resistance; it also acts as additional adhesive. Phenol-resorcinol-formaldehyde (PRF) glue is then often used together with the bitumen to the extent of 1–2%. For lamination common adhesives are polyvinyl acetate (PVAC) and waterglass glue, again typically 1–2%.

Fire retardants are used in most of these products. Common are whey, borates, ammonium sulphates and phosphates, and cement. Whey counteracts fire by releasing nitrogen when heated. Ammonium sulphates and phosphates release ammonia and water, borates release water. Cement being a mineral material is incombustible. Extent of fire retardants vary from 5–25%.

Anti fungal agents are added to some products. This can be soda waterglass cement, aluminium sulphate (alum) and borates. The effect of soda waterglass and cement is to increase the alkalinity of the product.

Water repelling additives are for products to be used in exposed or humid conditions, especially products for the exterior sheathing of buildings. They include bitumen, paraffin wax, colophony and latex. Often several of these are used in combination.

14.9 MOSS AND GRASS MATERIALS

Basic info is found in Chapter 10.

Many moss and grass species have considerable potential as climatic materials. Loose fill, boards, blocks and matting of different grasses give quite good thermal insulation, often comparable to the more industrialized insulation products. Most plant fibres also have good moisture buffering properties, and some even have a high resistance to rot, such as flax, hemp, eelgrass and moss. Plant materials are naturally combustible and where there are fire requirements must either be treated with a fire retardant or clad with incombustible materials.

Plant products often make suitable thermal insulation because, in a dry state, they contain a high amount of air and have an elastic structure that limits settling. Straw, eelgrass, lichen and moss can be dried and used as loose fill. With grasses such as flax, hemp and nettles the fibres are used to make mats or boards after removal of fruits and leaves. Additional glues are then most often added. Grasses can also be used as a source of cellulose based insulation (see page 289).Table 14.9

For air regulating purposes these materials are often used as felt strips or compressed loose fill for sealing of gaps between windows, doors and the building fabric. This is a critical part of the structure and needs high durability. Materials used in this way are flax, hemp, moss and fibres from nettles.

Ecologically speaking, grass materials are very attractive. They are either renewable resources that are wild or by-products of agriculture and food production. However, some of the glues, flame retardants and fungicides used have a doubtful environmental profile. In many cases, they will be as for the wood-based products (see page 280).

The energy used in the production processes varies considerably from product to product, but it is generally lower than that of similar products in other materials. Exceptions include insulation products glued with large amounts of synthetic compounds.

Pollution arising from the different levels of production, usage and waste is relatively small. The ability to store carbon should also be accounted for. During construction plant products often cause some dust and the wearing of simple masks would be advisable. Dust from hemp and cotton is problematic. In an indoor climate, plant materials

Table 14.9 *Acclimatizing qualities of moss and grass materials*

Material	*Composition*	*Areas of use*
Turf[1]	Earth with living grasses	Thermal insulation, sound insulation
Straw, loose fill[2] and bales	Stalks, possibly mixed with clay	Thermal insulation, sound insulation, moisture buffering
Straw softboards	Stalks, glued by natural ingredient, often covered with a layer of cardboard	Thermal insulation, sound insulation, moisture buffering
Grass fibres, matting and felts	Defibrated plant fibres, glued with polyolefins or polyesters (melting fibres), additives[3]	Thermal insulation, sound insulation, moisture buffering
Linseed oil putty	Linseed oil, stone flour	Sealing of joints
Moss	Whole plant	Sealing of joints, thermal insulation, moisture buffering
Peat, loose fill	Crumbled and dried peat, lime	Thermal insulation, sound insulation, moisture buffering
Peat, matting and soft boards	Compressed peat, matting are sewed inn between sheets of paper	Thermal insulation, sound insulation, moisture buffering
Cellulose fibre, loose fill	Recycled cellulose fibre, borax, boric acid	Thermal insulation, moisture buffering, sound insulation
Cellulose fibre, matting	Recycled or virgin cellulose fibre, glued with polyolefines or polyester (melted), additives[3]	Thermal insulation, moisture buffering, sound insulation
Cellulose building papers and sheets	Recycled or virgin cellulose, sheets are laminated with polyvinyl acetate etc. possible additives of latex, bitumen etc.	Vapour retarders, air barriers, wind barriers

[1] Discussed in Chapter 15, Surface materials.

[2] Thatching is dicussed in Chapter 15, Surface materials.

[3] Se page 280.

often have good moisture regulating properties and represent no known hazards with regard to emissions. However, additives may change this picture. Pure products can be either burned for energy recovery or composted after use; when composted, special care should be taken to avoid eutrophication of groundwater. For products containing adhesives, special waste treatment and incineration is required.

14.9.1 Grass plants

There are many different types of grass which can be used as climatic materials in the form of loose fill, matting or boards; e.g. wheat, rye, barley, oats, elephant grass, cotton, hemp, nettles, maize, reed, flax and eelgrass. Even common grass (*monocotyledonous*) can be used to make fibres for insulation products.

Loose fill consists of chopped stalks or fibre mass. Fibre products often have flame retardants and fungicides added, e.g. borates and are blown in. With chopped straw, lime is often added to repel vermin and reduce the risk of attack by fungus. It can also be stabilized with clay which besides improving resistance to rot also prevents settling.

14.19

Making blocks of straw loam in the Danube delta (Romania).
Source: Soare.

This method is often referred to as *lightweight straw loam*. Straw bale building can be seen as a hybrid where the loose mass is bound into 'elements' by the baling wires or strings.

LIGHTWEIGHT STRAW LOAM

A mix of straw and clay is rammed directly into the wall, or produced as blocks (which can later be built up with a clay mortar) (Figure 14.19). The straw loam is produced as follows:

1. All clays can be used. The clay is dried, crushed and poured into a tub of about 200–300 litres, ten times as much water is added and mixed well in. A motorized mixer can be used or the work can be done by hand. About 2% sodium waterglass is added to reduce the surface tension, so that the water can more easily penetrate the clay particles. This reduces the amount of water required and shortens the drying time. The clay should lie in the water for two hours. If using wet clay, it should be laid in water so that it is just covered and left for 24 hours.
2. The mixture is tested: 1 dl of the mixed clay gruel is poured evenly onto a piece of glass. The diameter is measured. If it is much less than 15 cm, it needs more water. If it is much more, then it needs more clay.
3. The clay gruel is poured onto the straw until it is totally drenched. In order to increase thermal insulation, straws with rigid shoots are preferred, since they do not deform easily, and hence keep air trapped inside.
4. The mixture is put into moulds to form blocks, or rammed into simple movable shuttering on either side of a timber frame wall, 30–60 cm thick. Before ramming, the timber framework – the structural part of the wall – is covered with clay as a sort of impregnation. The mixture must not be rammed hard. The middle is pushed down with the foot, whilst the edges are given more pressure: they can be beaten down with a piece of wood. The more compressed the mixture is, the stronger the wall, but with a corresponding reduction in thermal insulation. The different layers need to overlap each other when rammed within the shuttering. The holes left after

removing the shuttering are filled with clay. The drying time during the summer is between six and eight weeks, depending on the weather.

STRAW BALES

Bales of straw stacked on top of each other represent an economical and effective thermal buffer. In smaller constructions the bales can be load bearing, but use as frame infill is more common. Two-string bales are usually 36 × 46 × 92 cm and weigh about 20 kg, whilst 3-string bales are 41 × 58 × 114 cm with a weight of over 30 kg. Both dimensions and weight can vary depending upon the straw type, the baling equipment and the pressure used. The bales must be properly dry (10–16%) with no sign of mould or rot. Additional rot resistance can be achieved by dipping the bales in a solution of 5% waterglass, thin runny clay or lime gruel. This also improves fire resistance. All fresh straw has a thin waxy surface layer that breaks down over time. This prevents rendering from adhering to the straw, so straw should be stored for a year before use.

Bales are stacked up on each other and coursed like normal brickwork. Between courses, 70 cm long stakes can be inserted to hold them together. Extra reinforcement is used at corners and around openings. After two to four weeks the walls can be clad with a wire mesh and rendered, either with hydraulic lime plaster or a clay-based plaster, usually in three to four layers. Rendered straw structures are non-flammable. On very exposed sites, rendered surfaces must be protected by an extra outer skin such as timber panelling.

Building with straw bales was very popular in the USA until after the Second World War. They were used for everything from schools to aircraft hangars. In the early 1980s, a 75-year-old school built of straw was demolished in Nebraska, and the straw was undamaged and fresh enough to be used as cow fodder. Such relatively unexpected experiences have led to a renaissance of straw bale building in Canada, USA and Europe (Figures 14.20 and 14.21).

14.20

Walling with straw bales in a timber frame construction. Architects: Gaia Tjøme. Photo: Grethe Hald.

14.21

Straw baled kindergarten at Kongsberg Norway. Architects: Gaia Tjøme, 2007.

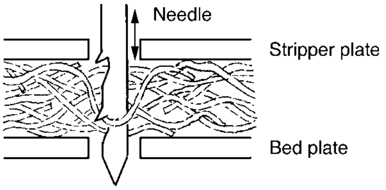
Matting and felt can be produced by binding fibres or stalks together with galvanized wire or by glueing, needle-punching or weaving together.

Hemp, flax and stinging nettles provide good fibres. The fibre fraction in mixed grasses produced on ordinary grassland is also very usable. With flax and hemp one normally uses the shorter fibres that are discarded during the production of textiles. The fibres are usually treated with flame retardants and fungicides. Hemp products have a natural resistance to fungal and are usually only treated with soda as a fire retardant (Figure 14.22).

14.22

Insulating with hemp matting.

Source: Camilla Høyem, Thermo-hanf.



14.23

Needlepunching of matting makes the use of glue unnecessary.

In needle-punching, fibres are filtered together into airy, elastic insulation mats (see Figure 14.23). Glued products are more common, and usually consist of polyolefin (e.g. polypropylene) or polyester (e.g. polyethylene terephthalate) fibres or fibres produced from maize starch (3–18% by weight) melted into the fibre mass (thermal bonding). Starch glue produced from potatoes or maize can also be used. The fibre mats are used in the same way as those of mineral wool or wood fibre.

Denser felt products and strips for sealing joints are usually produced by filtering or weaving the fibres together. These are often also used for sound insulation on floors.

Traditional reed mats are produced from stalks bound together with galvanized string or wire. Reed mats can be used as thermal insulation and as reinforcement in concrete walls. When rendered, the mats are also used as false ceilings.

Boards can be produced from straw in a mould with the stalks lying at right angles to the direction of the board. By exposure to pressure and heat, natural glueing agents in the straw are released and bind the board together. This process is stimulated by adding laccase. Porous boards have only moderate thermal insulating qualities, approximately equivalent to woodwool cement. Under damp conditions they will be exposed to attack by fungus. Straw boards can be produced with different densities (see page 344).

The first insulation boards made of straw were produced as early as the 1930s. They were made in thicknesses of 5–7 cm, under low pressure, reinforced with cross-wires and covered with paper.

Linseed oil putty is produced from the seeds of the flax plant. In addition to linseed oil, it consists of stone flour, such as chalk, heavy spar, powdered fired clay, powdered glass, etc.

Linseed oil putty is the only alternative to plastics-based mastics and window putties. It is environmentally much sounder than the alternatives, with no negative effects during production or use. As a waste product, it can be composted as long as no additives (such as lead) have been mixed in to improve its elasticity. The elastic qualities of the putty can be preserved for some time by painting with oil-based paint. Despite this, the putty will eventually harden and begin to crumble. Linseed oil-based putty must not be used in contact with damp lime or cement surfaces.

14.9.2 Moss

14.24

Log wall sealed with moss.

Moss has been used to seal joints in timber buildings for hundreds of years: between the logs in log constructions, around doors and windows and in other gaps (Figure 14.24). The moss has to be used as soon as it has been picked, because it hardens and loses its elasticity as it dries out. It can be boiled before use to reduce the amount of substances subject to attack from micro-organisms. But at the same time, natural antiseptic phenolic compounds found in some mosses can be lost.

Moss stops air penetration when compressed, and it is very hygroscopic. It can absorb large amounts of damp without reaching the critical level for the materials next to the moss.

Two types of moss are especially good in construction: *Hylocomium splendens* and *Rhytriadiadelphus squarrosum*. The latter is considered best, as it can last up to 300 years as a sealing material in a log wall without losing its main functional properties.

14.10 BOG PEAT

Peat has been used a great deal as an insulating material and moisture regulator in its natural state or as processed loose material, granules, mats or boards. These days, insulation products of peat are again being produced in Sweden.

Peat usually consists of decayed brushwood, plants from marshes, algae and moss. For building, the most important peat is found in the upper light layer of a bog and has not been composted. Older, more compressed and composted peat from deeper in peat bogs can be used in certain circumstances, but it has a much lower insulation value. Totally black, dense peat is unusable.

There is very little risk of insect and fungus attack in dry peat, as long as it is not built into a damp construction. Peat contains small quantities of natural impregnating toxins such as alcohol. It also has a low pH value (3.5–4), so it retards the spread of bacteria and protects against fungus.

The availability of peat as a resource is quite large but very regional. It is a semi-renewable resource, in the sense that new peat is continually but very slowly being formed from decaying vegetation. Extracting peat easily destroys a wetland environment, as well as releasing large quantities of methane CH_4, which is a very potent greenhouse gas.

Peat products can have a long lifetime, but acids in the peat can attack fresh cement mortar. In the indoor climate, peat regulates moisture well. Waste peat can be used directly for soil improvement or combusted for energy production.

Peat blocks are based on peat rich in moss and can be cut from bogs as blocks, dried and used as thermal insulation. It is easily trimmed by sawing for building into walls.

Peat loose fibres are made from dried, ground peat with a little lime added (about 5%) and can be used as loose thermal insulation in floor construction and walls. They are usually blown into the structure in the same way as other loose fill materials.

PEAT AS EXTERNAL WATERPROOFING

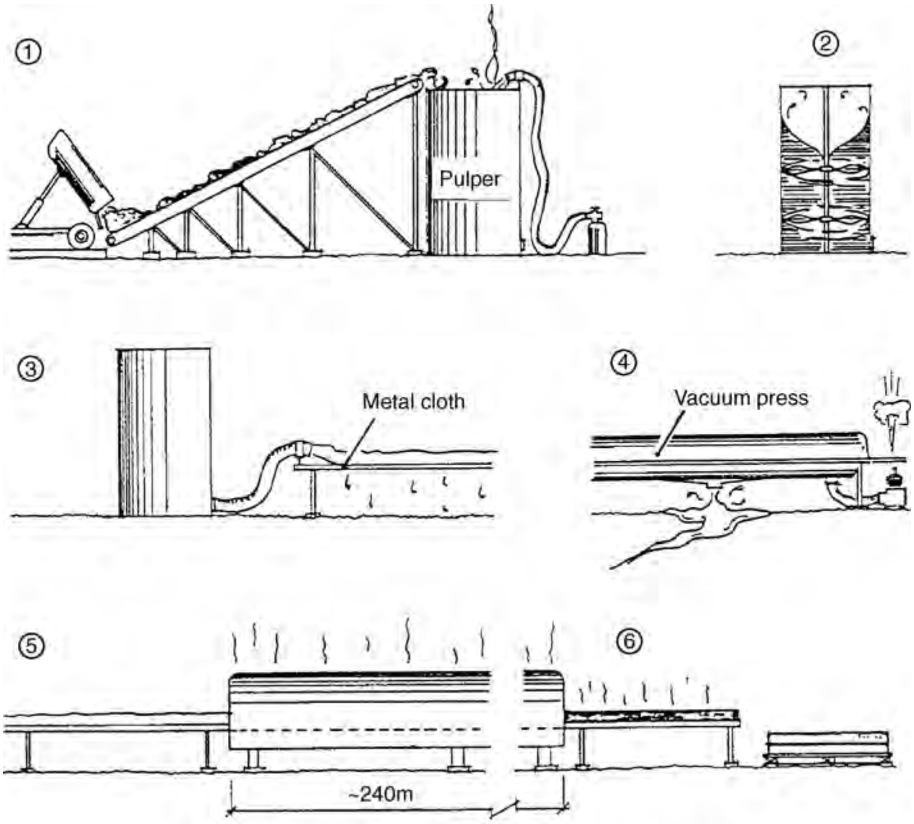
A special form of denser bog peat, called *rose-peat*, has often been used as the sealing material in dams. At the silver mines of Kongsberg in central Norway, dams of this peat are still watertight after being in use for 150 years. It is probably also suitable as a moisture barrier for foundation walls. Its sealing ability is due to the fact that it can absorb and hold large quantities of water.

The rose-peat, which is dark brown and available in most bogs, consists mainly of rotten leaves, and is found below the level of the roots in the bog. The plant fibres have to be visible, but the structure broken down. When a piece is rubbed between the fingers, it leaves a thick fatty layer on the skin, like butter. If the peat contains enough fibre, it feels rough. If it contains too little fibre, it feels smooth, like soap. The peat is cut out in cubes of 12 × 12 × 12 cm, often going down several layers before water fills the hole.

The rose peat must not dry out and should be used as quickly as possible, but its properties can be preserved for up to a week in damp weather by covering it with leaves and pine needles. Its use must be limited to frost free situations.

Peat matting consists of peat fibres sewn between layers of paper.

Peat boards are made in thicknesses of 20–170 mm. Their properties as a thermal insulation are very good, and can compete with mineral wool or cellulose fibre. The most widespread method of production begins with the peat being taken to a drying plant where it is mixed in warm water (Figure 14.25). It is then removed from the water, which is allowed to run off, leaving a moisture content of 87 to 90%. The mass is then put into a mould in a drying kiln to dry to 4 to 5%. To achieve different densities, different pressures can be applied. The whole process takes about 30 hours.



1. The harvested peat is mixed with warm water in a pulper.
2. The peat is carefully divided up in the pulper without destroying its pore-system.
3. The peat mass is sprayed out onto a metal cloth, to a specific thickness.
4. The water form the pores is pressed out.
5. The peat dries and hardens in a heat chamber.
6. The slab is divided into the required size.

14.25

Pressing peat slabs using the wet production method.

Source: Brännstrmetal.1985.

A dry production method can also be used. The peat is then pressed directly into moulds so that the damp is driven out of it. By warming it to 120–150 °C with no air, its own binders and impregnating substances are released. This is equivalent to its charring temperature, so the boards become fire resistant. There is also no need for added binders. This dry method of pressing came into use between 1935 and 1940 in the former Soviet Union. The method requires a relatively large amount of energy for the drying and setting processes, but this can be reduced to a certain extent by using solar energy for preheating.

14.11 CELLULOSE

Basic info is found in Chapter 10.

Cellulose products can be generated from a wide range of plants, but most commonly from timber. Cellulose is used in corrugated insulation boards and papers for air tightening vapour retarders and wind proofing membranes. Loose fill thermal insulation of cellulose was patented for the first time in England in 1893. It was made of shredded newspaper containing a fire retardant and a water repellent. Loose cellulose fill also has valuable properties as acoustic insulation. Most cellulose products regulate humidity well – suggesting that a room well filled with papers and books goes a long way towards providing a sufficient humidity buffer for a house (Derluyn *et al.*, 2007).

Thermal insulation of recycled cellulose fibre is usually treated with fire retardants and fungicides and is used on site as loose fill (Figure 14.26). The proportion of these additives is often as high as 18–25%. The most commonly used compounds are boric acid and borax. The fibres also contain traces of silica, sulphur and calcium from fillers in the initial paper waste.

Recycled cellulose fibre can also be used in the production of matting by adding an adhesive (often being lignosulphonates, a by-product of the cellulose industry). Jute may be added as reinforcing, plus wood resin as water repellent. As fungicide, a mixture of ammonium phosphate and tannin can be used as an alternative to borates. These mats are fairly stiff. A more flexible type is produced from virgin cellulose, with up to 9% polyester (e.g. polyethylene terephthalate) or polyolefine (e.g. polypropylene) fibre melted in (thermal bonding). Virgin cellulose is also formed into cellulose strips which can be used as joint fillers between window and door frames and the building fabric.

Resources for most products are unproblematic; energy use is initially low, though substantially higher for virgin cellulose products, especially when thermal bonding with synthetic fibres is used. Loose-fill cellulose fibre has been widely used as building insulation since the 1920s, and the material's durability is good as long as it has been placed in the walls or roof space in the correct way. This involves applying a high pressure when blowing in the fibre, to avoid settling later on. At densities above 70 kg/m^3 no settling should occur (Hansen, 2000).


14.26
Loose fill of cellulose fibre.

In the production process workers can be exposed to dust made up of paper and fine particles of borax and boric acid. Exposure to dust will also occur at the building site, but once installed correctly the fibres should cause no problems for those using the building. Cellulose fibre products have good moisture regulating properties and are less susceptible to mould than the mineral wool alternatives.

The products can be re-used. Energy recovery of products treated with fire retardants requires mixing with other more combustible wastes (Krogh *et al*. 2001). As waste, borates can seep into the earth and ground water and must be handled specially. Products with ammonium phosphate and tannin can be composted, but effluents contain eutrophicating substances.

FOAMED LIGNIN

Lignin is a residual by-product of the cellulose industry; these days, used almost only for energy. High-value insulation products of foamed lignin are being developed (Lund, 2003; Wimmer *et al*., 2001; Stocklund, 1962). Conventional baking powder can be used to expand the product at between 60 and 90 °C. Energy use for production is approximately 10% of that needed for mineral wool products. It needs no fungicides, has no emissions, and can be composted or burned after use.

Cellulose building paper is usually manufactured from recycled paper and unbleached sulphite cellulose. It can also contain up to 20% wood pulp. Boards are manufactured by laminating the sheets of paper together to a thickness of 2 to 3 mm, most often with polyvinyl acetate adhesive (PVAC), about 3% by weight. Waterproofing and water-repelling substances are added to all of these products, e.g. bitumen, latex and paraffin wax. Cellulose building paper is also combined in laminates with, for example, polyethylene and aluminium and can be supplied with a matrix of polyester as reinforcement.

Durability is good. Pure cellulose paper and laminated weather-proofing boards (with natural latex) can, most probably, be recycled into new cellulose products, e.g, loose fill thermal insulation. Wastes from other products are best suited for energy recovery or use as a low quality cellulose fill in asphalt, etc.

14.12 MATERIALS BASED ON ANIMAL PRODUCTS

Basic info is found in Chapter 11.

Climatic materials obtained from animals are primarily hair, wool and hide (Table 14.10). Animal fibres are high quality thermal insulators and very good moisture regulators. Reindeer skins have been widely used as thermal insulation, especially amongst the Lapps. The most widespread use of animal products today is as ingredients for wool-based building papers and thermal matting. A slightly more peripheral product is crushed mussel shells providing thermal insulation and cappillar breaking layer in slab-on-ground foundations.

Woollen matting can contain varying quantities of recycled wool. The product often contain borates (approximately 1% by weight) against insect attack. In some cases biocides such as pyrethrin and chlorinated compounds like sulcofuron are added for additional protection against

Table 14.10 *Climatising qualities of animal products*

Material	*Composition*	*Areas of use*
Mussels	Shell	Thermal insulation, capillary barrier
Wool, loose fill	Wool, possibly partly recycled; biocides	Thermal insulation, sound insulation, moisture buffering, sealing of joints
Wool, matting and felt	Wool, possibly partly recycled; glued with polyesters (melting fibres), biocides	Thermal insulation, sound insulation, moisture buffering, sealing of joints
Wool, building paper	Wool, possibly with cellulose (recycled) or bitumen added	Sound insulation (impact noise)

moths. As a binder, fibres of polyester (e.g. polyethylene terephthalate) are melted in, in amounts around 10% by weight, but the product are also produced by needle-punching (see Figure 14.23).

Woollen felt is used as a sound insulation between floor joists and as a thermal insulation around water pipes. Felt strips are also often used for sealing gaps between windows, doors and the building fabric. Woven sealing strips are used in windows. They become hard when painted, and damp can cause them to shrink and loosen from their position.

Wool-based building paper consists of a good deal of recycled paper, but the woollen content must not be lower than 15%. Wool building paper is soft and porous and is often used as step sound insulation.

Wool is broken down at a temperature of over 100 °C and by fat, rust, petroleum, alkalis and oil. The material does not burn easily, but smoulders when exposed to fire.

The raw material for most woollen products is rejected wool from abattoirs, which would otherwise be thrown away. If sheep farming were to be done solely for wool, then the environmental impact, especially associated with growing of their fodder and emissions of the greenhouse gas methane from digestive processes, would be high – however, seen largely as a by-product, the equation looks more favourable.

Animal products can be considered problem-free in the user phase. Additionally, woollen products help to even out moisture changes in the indoor air as well as within construction. However, the use of toxic additives makes it necessary to dump the waste at special tips. Pure products of wool can and should be composted. This should take place at controlled sites since normal dumping will lead to increased nutrients seeping into the ground water from the tip.

14.13 MATERIALS BASED ON RECYCLED TEXTILES

Basic info is found in Chapters 9, 10 and 11.

Each year, thousands of tons of textiles, including clothes, are thrown away. On rubbish dumps they decompose, emitting large quantities of the greenhouse gas methane. However, products based on recycled textiles are now becoming quite common (Figure 14.27). Discarded textiles are collected, and synthetic textiles are removed so that the final product contains over 95% wool and cotton. It is shredded and then heated to 120 °C while fibres of polyester (10–15% by weight) are melted in as a binder. Ammonium phosphate fire retardant may be added.

It has been estimated that in the case of Norway, if all such waste textiles could be re-used in the form of insulation, this could cover up to 25% of the total building insulation market. This very positive resource-perspective is compromised somewhat by the fact that the added polyester is an oil-based product. With mostly natural fibres, the moisture buffering properties are good. The material can probably be recycled into the same product again, but as waste it may have to be especially disposed of depending on the substances added.

14.27

Insulation matting of recycled textiles.
Source: Rolf Jacobsen/Ultimat.

ENVIRONMENTAL PROFILES OF CLIMATIC MATERIALS (TABLE 14.11)

RULES OF READING

The volumes of materials and the loss factors are estimated on the basis of conventional practice.

The effects of additional material properties, such as thermal storage capacity and structural properties, are not included.

Calculation of global warming potential GWP include carbonatation (50 years), storing of carbon dioxide (50 years) and emissions from final incineration of products based on fossil fuels. The storing of carbon is calculated from net weight of material, (exclusive loss and renewal).

The environmental evaluations are rated best = 1, average= 2 and worst alternative = 3. The *Environmental potential* columns indicate potentials for recycling and local production. The final environmental profile is suggested on the basis of subjective judgement from the author and is open to debate. On the basis of information in Table 1.4 and Table 2.8 alternative evaluations can be made. Also note the results in the GWP column, since global warming potential is often considered as a relevant overall indicator for environmental impact.

THERMAL INSULATION

The estimates and evaluations are made per m^2 of insulation layer with R-value 3.75 (=150 mm with specific thermal conductivity 0.04 W/mK) and a house lifespan of 50 years. All insulation materials are assumed to last this long without renewal, except straw bales which must be renewed once.

WIND BARRIERS, VAPOUR MEMBRANES/AIR BARRIERS, DAMP-PROOF COURSES AND FLASHINGS

The estimates and evaluations are made per m^2 layer and a house lifespan of 50 years. With the exception of most flashings all materials are assumed to last this long without renewal. This might however be a too optimistic approach.

Table 14.11a *Thermal insulation*

Material	*Specific thermal conductivity [W/mK]*	*Specific thermal capacity [kJ/kg K]*	*Loss factor [%]*	*Quantity needed for thermal resistance R = 3,75 [kg/m^2 50 years]*	*Global warming potential GWP [kg CO$_s$-equ./m^2 50 years]*	*Environmental evaluations*						
						Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
						Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Still air	0.024	1.0	–	–	–	–	–	–	–	–	–	–
Water	0.5	4.2	–	–	–	–	–	–	–	–	–	–
Dry snow	0.05		–	–	–	–	–	–	–	–	–	–
Wet snow	0.47		–	–	–	–	–	–	–	–	–	–
Aerated concrete blockwork, 500 kg/m^3	0.08	1.0	10	165	**68**	3	3	2	2			**3**
Expanded perlite, untreated, 80 kg/m^3	0.05	1.0	1	15	**8.5**	2	2	2	1	✓		**2**
Foam glass boards, 110 kg/m^3	0.043	1.1	10	20	**25**	2	3	2	2			**2**
Glasswool, 18 kg/m^3	0.038	1.0	5	2.5	**4.5**	2	2	3	3			**2**
Rockwool, 30 kg/m^3	0.038	1.0	5	4.5	**7.5**	2	2	3	3			**2**
Expanded clay pellets, 450 kg/m^3	0.11	1.0	1	185	**66**	3	3	2	1	✓		**3**
Foamed polystyrene EPS, 20 kg/m^3	0.038	1.5	10	3.1	**22**	3	3	3	3			**3**
Foamed polystyrene XPS with HCFC's, 30 kg/m^3	0.036	1.5	10	4.5	**113**	3	3	3	3			**3**
Foamed polyurethane, 35 kg/m^3	0.028	1.2	10	4.1	**68**	3	3	3	3			**3**
Cork boards, untreated, 130 kg/m^3	0.04	1.7	10	21	–**4.0**	1	3	1	1			**1**
Wood shavings, refined, 80 kg/m^3	0.045	2.1	1	14	–**7.5**	1	1	1	1	✓	✓	**1**
Wood fibre, loose fill, 45 kg/m^3	0.039		1	6.9	–**1.5**	1	2	1	1	✓		**2**
Woodfibre matting with starch glue, 45 kg/m^3	0.039	2.1	5	7.2	**1.5**	1	2	1	1			**2**

Table 14.11a *(Continued)*

Material	*Specific thermal conductivity [W/mK]*	*Specific thermal capacity [kJ/kg K]*	*Loss factor [%]*	*Quantity needed for thermal resistance R = 3,75 [kg/m^2 50 years]*	*Global warming potential GWP [kg CO_s-equ./m^2 50 years]*	*Environmental evaluations*						
						Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
						Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Wood fibre matting with polyolefines, 45 kg/m^3	0.039	2.1	5	7.2	**3.5**	2	3	2	2			**2**
Porous wood fibre boards, wet process, 130 kg/m^3	0.043	2.1	10	23	**18**	1	3	1	2			**2**
Porous wood fibre boards, dry process, 130 kg/m^3	0.043	2.1	10	23	**15**	2	3	3	3			**2**
Matting of flax fibre, with polyolefines, 25 kg/m^3	0.04	1.6	5	3.9	**5.5**	2	3	2	2			**2**
Matting of hemp fibre, with polyolefines, 25 kg/m^3	0.045		5	4.4	**4.0**	2	3	2	2			**2**
Straw bales, 90 kg/m^3, lifespan 25 years	0.052		5	37	**−13**	1	1	1	1		√	**1**
Recycled cellulose, loose fill, 45 kg/m^3	0.042	1.8	1	7.2	**−4**	2	2	3	3	√		**2**
Matting of fresh cellulose fibre, with polyolefines, 45 kg/m^3	0.04	1.9	5	7.1	**3.0**	2	3	2	2			**2**
Matting of wool, with polyesters, 18 kg/m^3	0.04	1.3	5	2.8	**2.0**	2	2	2	2			**2**
Matting of recycled textiles, with polyesters, 25 kg/m^3	0.038		5	3.7	**5.0**	1	2	2	2			**2**

Table 14.11b *Wind barriers, vapour membranes/air barriers, damp-proof courses and flashing*

Material	*Durability [years]*	*Loss factor [%]*	*Quantity of material needed [kg/m^2 50 years]*	*Global warming potential GWP [kg CO$_s$-equ./m^2 50 years]*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Wind barriers											
Plasterboard with silicone, 9 mm	50	15	9.3	**2.1**	2	2	1	2			**2**
Polyethylene sheeting, 0.15 mm	50	7	0.2	**1.0**	3	1	2	2			**2**
Polypropylene sheeting, 0.15 mm	50	7	0.2	**1.0**	3	1	2	2			**2**
Porous wood fibre board with bitumen, 12 mm	50	10	3.1	**1.9**	3	3	3	3			**3**
Cellulose paper with bitumen, 0.5 mm	50	10	0.6	**0.2**	3	2	2	3			**2**
Cardboard sheeting with latex, 2 mm	50	10	1.6	**−0.3**	1	2	1	1	√		**1**
Vapour membranes/air barriers											
Polyethylene sheeting, 0.15 mm	50	7	0.2	**1.0**	2	2	2	2			**2**
Polyvinyl chloride sheeting, 1.0 mm	50	7	1.4	**5.1**	3	3	3	3			**3**
Hard wood fibre board 900 kg/m^3, 3.0 mm	50	10	2.9	**2.0**	1	2	2	1	√		**1**
Cellulose building paper, 0.5 mm	50	10	0.6	**−0.2**	1	1	1	1	√		**1**
Dampproof courses											
Slates, 5 mm	50	5	14	**0.2**	1	1	1	1	√	√	**1**
Bitumen applied direct, 3 mm	50	5	3	**10**	3	3	3	3			**3**
Bitumen sheeting, 2 mm	50	10	2.2	**5.5**	3	2	3	3			**3**

Table 14.11b *(Continued)*

Material	*Durability [years]*	*Loss factor [%]*	*Quantity of material needed [kg/m^2 50 years]*	*Global warming potential GWP [kg CO_s-equ./m^2 50 years]*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Polyethylene sheeting, 0.5 mm	50	7	0.6	**2.9**	2	2	2	2			**2**
Polyvinyl chloride sheeting, 0.9 mm	50	7	1.3	**4.0**	3	3	3	3			**3**
Flashing											
Galvanized steel, from ore, 0.6 mm	30	15	7.9	**17**	2	1	1	2	√		**1**
Aluminium, from ore, 0.6 mm	50	15	1.9	**29**	1	2	1	1	√		**1**
Copper from ore, 0.6 mm	50	12	5.9	**36**	3	3	2	3	√		**2**
Lead from ore, 1.5 mm	25	15	39	**43**	3	3	3	3	√		**3**
Polyvinyl chloride sheeting, 1.5 mm	25	10	4.5	**20**	2	1	2	2			**2**

Table 14.12 *Technical properties of secondary climatic materials*

Materials	*Technical properties*	
	Specific thermal conductivity (W/mK)	*Specific thermal capacity (kJ/kgK)*
Metals		
Steel	58	0.4
Non-metallic minerals		
Concrete	1.75	0.92
Portland cement plaster	1.15	0.92
Lime cement plaster	1.05	0.94
Lime plaster	0.9	0.96
Lime sandstone	0.7	0.88
Stone		
Granite	3.5	0.8
Limestone	2.9	0.88
Brick		
Well fired, massive	0.7	0.92
Well fired, perforated	0.6	0.92
Light/medium fired, massive	0.65	0.92
Earth, pisé and adobe		
Fibre content 10 kg/m^3	0.96	1.0
Fibre content 40 kg/m^3	0.615	1.0
Fibre content 70 kg/m^3	0.420	1.05
Timber		
Perpendicular to the fibres	0.12	2.1
Parallel with the fibres	0.35	2.1

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15 Surface materials

The main purpose of surface materials is to form a protective layer on a building's structure. Through their hardness and durability they must withstand wear and tear on the building, from hard driving rain on the roof to the never-ending wandering of feet on the floor. Sheet materials can also have structural and climatic functions such as bracing, windproofing, moisture control, noise protection, etc. Certain structures in brick, concrete and timber are in themselves surface materials and, therefore, do not need further treatment. Surface materials are otherwise used in roof covering, internal and external cladding, and on floors (Table 15.1).

Because surface materials are used on large exposed areas, it is important to choose materials that do not contain environmentally contaminating substances which may wash into the soil or ground water or emit unhealthy gases into the interior of the building. They should be both physically and chemically stable during the whole of their lifespan in the building or at least be easy to renew.

Exterior cladding and roofing are the building elements that are most exposed to the forces of the weather. They must therefore be chosen with local climatic conditions in mind. Especially critical are inelastic and porous materials used on façades exposed to driving rain and frequent freeze–thaw cycles. We should remember that weather conditions may change as a result of the ongoing climate change. This will lead to generally increased risks in Northern Europe, and possibly to reduced building stresses farther south (Noah's Ark, 2006). Along coastlines weathering due to salt spray is likely to increase.

Surface materials need a long aesthetic lifetime. They must withstand wear and dirt without becoming unattractive. A wood floor with good surface treatment will, even if highly worn, develop a fine patina over time, whilst an enamelled steel surface that is dented, or a plasterboard that is slightly cracked, will need to be replaced almost immediately. Since exterior claddings also function as protection for the structure, membranes and insulation materials, it is an advantage if any damage to these can be quickly noticed. Claddings of aluminium and polyvinyl chloride can conceal problems until they fail disastrously.

The roofing of the building is its hat; it must protect the building from everything coming from above, which sets requirements for how it is anchored, drained, and protected from frost, snow and ice. Most

Table 15.1 *Surface materials in buildings*

Material	*Roofing*	*External cladding*	*Internal cladding*	*Flooring*
Metals, sheets	Gu	Gu	Gu[1]	Lu
Cements/concretes; boards, sheets and tiles	Gu	Gu	Gu	Gu
Gypsum boards			Gu	
Calcium silicate sheets			Gu	
Plasters, cement based		Gu	Gu	
Plasters, silicate based		Gu	Gu	
Plasters, gypsum based		Lu	Gu	
Plasters, sulphur based		Nu	Nu	
Slate/stone	Gu	Gu	Lu	Gu
Fired clay; bricks and slabs	Gu	Gu	Gu	Lu
Ceramic tiles		Lu	Gu	Gu
Compressed earth slabs			Lu	
Loam plasters		Lu	Lu	
Bitumen products; sheeting	Gu	Lu		
Plastic products; boards, sheets and tiles	Gu	Lu	Gu	Gu
Living plant surfaces, turf and climbers	Lu	Gu		Nu
Solid wood	Lu	Gu	Gu	Gu
Straw	Lu	Lu		
Plant-based building boards, sheets and tiles		Lu	Gu	Gu
Building boards from domestic waste			Lu	

Abbreviations: Gu: In general use; Lu: In limited use; Nu: Not in use.
Empty spaces indicate that use is irrelevant.

[1] Industrial buildings.

roofing materials have a different material layer beneath them which helps to waterproof the building.

The external cladding has a similar task in many ways, but the demands are not quite as high, especially as far as waterproofing is concerned. However, in areas of hard rain and strong winds, very durable materials are required. Façades exposed to strong sun also need special attention.

The internal cladding has lower demands with regard to robustness in most types of rooms. The main factor is that damage can be caused by the use of the building, although the material in a ceiling does not need to have the same strength or resistance to wear and tear as that in the walls. Internal surfaces should have a higher level of finish, to give it a feeling of comfort and be pleasant to the touch. Cleaning should also be easier with these finishes. However, surface finishes should not block a material's ability to regulate indoor humidity. This is essential for a good indoor climate (see Chapter 14, page 245). This is a function that is as

Table 15.2 *Washability of floor materials*

Flooring material	*Cleaning factor*
Cork	7
Timber cubes	6
Timber	5
Concrete slabs	5
Asphalt	5
Bricks	5
Linoleum	4
Parquet	4
Terrazzo	3
Stone slabs	3
Ceramic tiles	2
Polyvinyl chloride PVC	2

Note: The lower the cleaning factor, the more easily the surface is cleaned.

important as robustness, and implies that hygroscopic materials should be preferred wherever there is no special risk of water spills or dirt.

The floor covering is the one surface in a building that is normally most exposed to wear. It is the part of the building with which the occupants have most physical contact, so comfort factors such as warmth and hardness must also be taken into account. Technical properties required in a floor material are that it should:

- possess a low thermal conductivity.
- not be too hard and stiff.
- not be slippery.
- demonstrate a low risk of electrostatic charge (Table 15.3).
- be easy to clean (Table 15.2).
- contain good acoustic properties.
- retain good moisture regulating properties.
- include mechanical strength to resist wear and tear.
- be resistant to water and chemicals.

Many floor coverings, such as linoleum and cork tiles, which are not load bearing as such, need to be laid on a stable floor structure. The amount of moisture in the structural floor and its ability to dry out are therefore critical: the quicker it dries out, the sooner the floor covering can be laid.

FLOORING AND DAMAGE TO HEALTH

In the town of Steinkjer in central Norway, people complained of aching feet after moving into new houses. Their wooden houses had burnt down in a fire and had been replaced with houses with concrete floors covered with plastic tiles. The complaints developed into damage to muscles and joints. The hard floors were the cause.

In the same way, over hundreds of years horses in towns and cities suffered as a result of the paving under their hooves. As a result, they were often put out to graze much earlier than country horses, used to working on a softer surface.

Table 15.3 *The potential electrostatic charging in different materials*

Material	*Electrostatic charging (V/m)*
Timber, untreated	0
Timber, varnished	−20 000
Hard wood fibre board	+50
Plywood	−110
Chipboard	−250
Polyvinyl chloride	−34 000
Synthetic carpets	−20 000

'Bakers' illness' was once a common problem in bakeries with hard concrete and tiled floors. The floors were in direct contact with the ovens, which heated the floors by up to 30 °C. This continual high floor temperature gave bakers headaches and feelings of tiredness. One way to avoid this was by wearing wooden clogs, since wood is a bad thermal conductor. A more common and serious problem today is high thermal conductivity in floors, which can draw warmth from the feet. A concrete floor will almost always feel cold.

Floors made of materials that are bad electrical conductors such as polyvinyl chloride PVC create an electrostatic charge when rubbed, which attracts dust particles out of the air. This is one of the most likely reasons for 'sick building syndrome'.

Carpets and wallpapers are supplementary surface coverings and are discussed in the last part of this chapter.

15.1 METAL SURFACE MATERIALS

Basic info is found in Chapter 6.

There are metal alternatives for most surface materials. The products for cladding are usually produced as thin sheets and need to be mounted on a strong basis.

For many centuries, copper and bronze have been widely used on churches and other prestigious buildings. In the south-west of England, lead from local mines was, until recently, used as a roofing material. On Iceland, walls and roofs covered with corrugated iron imported from England have been part of the established building tradition since the 1890s. In modern buildings, sheeting of galvanized steel and aluminium is increasingly being used as roofing and as cladding on external walls. This is especially the case in large and commercial buildings where low maintenance is a priority requirement.

In industrial buildings the internal wall cladding is quite often of stainless steel. This is easy to keep clean and particularly well-suited for premises that produce food, for example. Flooring consisting of 6 to 8 mm thick cast iron tiles with a textured surface is popular in buildings used for heavy industry.

Historical examples of the internal use of metal sheeting are limited. One example is the notorious lead chambers of Venice that were used for jailing particularly dangerous criminals, such as the seducer Don Juan. The lead chambers were placed on roofs exposed to the sun, making them unbearably hot during the day and terribly cold at night.

Modern metal sheeting is mainly galvanized steel, aluminium, copper, zinc and stainless steel. For internal use, stainless steel dominates the market. These products are often anodized with a thin surface layer or painted with special plastic paints, usually containing epoxy, acrylates, polyester or polyvinyl chloride, the latter often mixed with phthalates. Copper, however, requires no surface treatment. Certain metals cannot be used together because the combination causes galvanic corrosion. For example, when mounting sheeting, iron or zinc nails or screws must not be used to fix copper, and vice versa. Rainwater from a copper roof must not be drained over iron or zinc, as the copper oxide produced will soon destroy the iron or the zinc.

From an ecological point of view, the use of metals should be reduced to a minimum. Reserves in nature are limited, and the production of metals requires high amounts of energy, usually based on fossil fuels; emissions of greenhouse gases and other severe pollutants during the production of metals are generally large.

Once installed, metal products cause few problems, but there can be a release of metal ions from external surfaces when washed by rain, which drain into the soil and ground water; lead and copper cause the most problems, while zinc can be a problem if used in large quantities. Using a lot of metal in a building can also increase electromagnetic fields inside it.

The durability of exterior metal claddings is moderate – best for aluminium and copper and quite low for zinc products, especially if exposed to sea air or polluted town air. Intact sheets can normally be re-used in their original form, but this is seldom done since they are often damaged, particularly during dismantling. The alternative would be material recycling achieved by melting them down. However, in this case there may be emissions from the coating treatments that are often applied, including dioxins from products coated with polyvinyl chloride. Powder-coated aluminium is not recyclable. Polluted and mixed waste must be disposed of at special facilities. It should not be mixed with waste for energy recycling, since the surface treatments can emit toxic gases.

15.2 NON-METALLIC MINERAL SURFACE MATERIALS

Basic info is found in Chapter 6.

Cementitious substances can be used to produce materials for all surfaces, either cast in situ as plasters or as prefabricated components, including units for cladding, underlay for floors and other basic elements.

The first concrete roof tile was made in Bavaria in 1844. Since the 1920s, concrete roof tiles have been in strong competition with clay tiles. Whether they can be as beautiful as clay tiles has always been a matter of debate. As early as the beginning of the twentieth century the Norwegian engineer Bugge advised: ‘Don’t spend much time putting concrete tiles on dwellings because their form is usually unattractive, and their colours, in particular, are most ungraceful' (Bugge, 1918). Colouring has improved somewhat since then, to the extent that it can be difficult to tell the difference between concrete and clay tiles. The concrete tile has taken on both the colour and form of the clay tile, but the difference is more apparent when ageing; the clay tile is usually still considered as having a more dignified ageing process.

In situ cast floors have a long history. They have been found in 7000-year-old ruins in the Middle East. The mixes were of pure lime; today they are cement-based or made of concrete slabs.

Mineral sheets consist of lime, cement or gypsum-based substances with other constituents added, such as reinforcing fibres. They are used widely as roofing sheets, exterior and interior claddings, as well as for wind bracing and subfloors. These products also have good acoustic and fire-resistant properties. Many of them are useful as interior claddings due to their humidity regulating properties. Fairly thick sheets will contribute usefully to the thermal mass and stabilize interior temperatures.

Plasters provide finished surfaces that often do not need further treatment. This is especially the case with lime plasters, which can be given a matt or polished finish. The treatment of walls with plasters also dates back thousands of years. As well as its function as a surface treatment, plaster can also be considered a highly valuable climatic material, as it can provide wind-proofing and moisture control.

The most relevant non-metal minerals have rich reserves but the extraction often entails heavy defacing of the environment, which can lead to changed water table levels and damage to biotopes. Products based on Portland cement and lime also entail large emissions of the greenhouse gas carbon dioxide during the calcination process. Part of this is later reabsorbed into the material through the building's lifetime, especially in the case of pure lime products. Pollution can be caused by a variety of additives to these products, both during production and if they are dumped after demolition.

Surface products based on non-mineral materials usually present no problems in the indoor climate. Some of the additives can entail a risk of unhealthy dust and fumes. If steel reinforcement is used, the electromagnetic fields in a building can increase. Many products can be reused if they are easy to dismantle. They are usually inert and can, if nothing else, be used as fill material. An exception is gypsum products that can degrade to polluting sulphur compounds.

15.2.1 Roofing

There are two main types of cementitious roofing: tiles and corrugated sheeting. Certain amounts of fibre must be added to both to give them the required tensile strength. Polymer emulsions or a coating of acrylic paint are often added to suppress efflorescence, provide colour and help seal sanded and textured surface finishes. More than any other concrete product, roofing needs particular care given to the proportions of the ingredients and the design of the sheeting or tile. One important aspect is that the finished product must have very low moisture absorption.

Concrete tiles (see later Figure 15.3) are usually made with about 25% Portland cement content. Other hydraulic cements can also be used. Sheets consist of up to 45% cement, and 5 to 10% silicate powder is often added. The rest is mostly sand, fibre and water. The fibre mixture can be natural fibres from hemp, sisal, steel, jute, reed, goat hair and cellulose, synthetic organic fibres from polyvinyl alcohol, polyacrylonitrile, polypropylene and polyester, or mineral fibres based on silica dust, steel, carbon, asbestos or fibreglass. Organic fibres are more easily decomposed. Research has, however, shown that even if this happens most of the strength is conserved (Parry, 1984). The reason for this is partly that the fibres play their most important role during the setting process; it is during this period that the dangers of damage through shrinkage are greatest. Roof sheeting was originally produced mainly with asbestos fibre, but this is now generally banned and has been replaced by other fibres mostly from cellulose and polyvinyl alcohol for health reasons, in a proportion of 2% by weight.

SMALL-SCALE PRODUCTION OF CORRUGATED SHEETING

The mix for corrugated sheeting is about 5 kg cement, 15 kg sand and 0.2 kg fibre, mixed well with water. The mix is poured into a mould where it hardens over 24 hours. It is then placed in a damp, solar-warmed plastic case to cure for a month, or laid in water to cure for at least seven days (the curing must not occur in dry air). After curing the sheets are dried (Parry, 1984).

The Intermediate Technology Group (IPDG) in England developed a production system for corrugated roof sheeting which is highly appropriate for small-scale production. The factory can produce 2000 tiles of 50 × 25 cm per week and needs four workers in a floor space of 25 m^2 with a courtyard of about 40 m^2. A factory that produces 20 000 tiles a week, employs 30 workers on a factory floor of 400 m^2 with a courtyard of 350 m^2. In this way one can produce roofing at three quarters of the price of corrugated metal sheeting. These have been produced for 20 years, and the lifespan of the sheeting is estimated at 50 years.

Environmentally speaking, cement-based roofing can be considered better than the metal alternatives. However, roof sheeting is more economical in terms of material use than roof tiles. All of the products can be re-used, but the sheeting can be more easily damaged under demounting.

15.2.2 Sheets for cladding

External and internal cladding as well as subfloors can be done with mineral sheeting. There are three main types of mineral sheeting for these applications: cement-based, calcium silicate-based and gypsum-based. In addition to the binder, they often contain fibrous reinforcement. The mixtures can also include polymer emulsions to suppress efflorescence and pigments to give colour. When the sheeting is used as internal cladding the joints must be filled. The filling material is, almost without exception, based on plastic binders, mainly polyvinylacetate or acrylate glues. Joints can also be covered by timber strips or the products can be tongued and grooved.

The energy needs and polluting emissions associated with production are large for the cement-based sheets, moderate for the gypsum products and low for those of calcium silicate. This is largely proportional to the calcium content.

In the finished buildings there are few problems with these materials, although asbestos may be found in older products. The use of plastic-based mastics and jointing between sheets for internal use could result in emissions of monomers and other organic substances that can reduce the quality of the indoor climate.

Robust sheets can often be re-used, especially if fillers are not used in the joints. However, by taping the joints with an easy removable, broad tape, before filling the sheets can be kept well preserved even then. Pure plasterboard will often be too weak to be re-used, but the material can be recycled as a 5–15% constituent in new material. The gypsum industry is, however, very centralized, which makes it economically unviable to recycle the products. Calcium silicate products can be crushed and recycled as aggregate in concrete. If finely ground, they can be used in mortars and plasters.

The waste is inert and can be used as fill, as can most cement products. If there are high levels of organic substances in the products, when they become waste they may increase the amount of nutrients seeping into the ground water. Sulphur pollution can develop from waste gypsum through decomposition by microbes; this can be reduced by adding lime.

Cement-based sheets for cladding are very similar to roofing sheets. They are strong and can be used externally without rendering as they withstand severe climate conditions. As reinforcement cellulose fibres and polyvinyl alcohol (PVA) fibres are much used, but also chippings from spruce or birch give good results, especially for interior use and in subflooring. The amount of wood chippings is then usually about 25% by weight. The cell content of the wood should be washed out by boiling or leaving the chippings in fresh air for a year. As a final treatment the chippings can have substances added which accelerate the setting of the concrete. Waterglass, calcium chloride or magnesium chloride can be used. The wood is left to lie in a 3 to 5% solution for a while and is then mixed with Portland cement and water, after which the sheets are formed in a hydraulic press for seven to eight hours, then set in a special curing chamber.

Calcium silicate sheets are used as both external and internal cladding. The sheets have very good fireproofing properties and offer slightly better thermal insulation than other mineral sheets. They also have good humidity characteristics. Calcium silicate sheets are produced by reacting up to 92% by weight of quartz with lime and with a little cellulose fibre as reinforcement. Vermiculite can be used as aggregate.

Plasterboard was first produced about 100 years ago. The sheeting is the most commonly used of all internal wall claddings, either painted or covered by wallpaper or thin fibreglass woven sheeting for painting. Gypsum products also have an important role as climatic products, for example as acoustic ceilings and wind barriers. Some products for windproofing have shown a tendency towards mould growth (Lisø *et al.*, 2007). For the same reason, it may be suspect to use plasterboard in bathrooms.

The standard products are manufactured from 95% gypsum with fibreglass reinforcement (about 0.1% by weight). Industrial gypsum, a by-product from coal-fired power stations, is commonly used in portions of up to 80% of the total. The following substances are also added to a total of about 1% by weight: calcium lignosulphate, ammonium sulphate and an organic retardant, usually trinatriumcitrate. The sheets are covered with thin cardboard glued with potato flour paste or polyvinyl-acetate adhesive. Pure gypsum sheeting is not particularly strong, but with more reinforcement added (e.g. wood shavings and recycled cellulose materials), the strength will increase. There are also products with granulated cork added, and even recycled tyre fibres (Eires *et al.*, 2007).

15.2.3 Plaster

Many cementitious plasters are available, depending upon the surface to be rendered and the actual climate conditions. The alternative binders are lime, waterglass, cement, gypsum and sulphur, as well as mixtures of these substances. Additives can make the plaster bind better or improve elasticity or thermal insulation; they include steel fibres, mineral fibres, perlite, hacked straw, or even hair from cows, pigs and horses. In polymer modified plasters polyvinyl-acetate is added, up to 5% by weight. Colour pigments can be added; these should be fine grained and resistant to alkalis; usually metallic oxides are used. For external rendering or rendering in rooms such as bathrooms, water-repelling, hydrophobic substances are most often added, such as silicone products. Sand is also added, its grain size depending upon the surface quality required and how many layers of plaster are to be used. The final ingredient is water.

Rendering is labour-intensive work, but the result has a long lifespan. Well-applied lime plaster can last from 40 to 60 years, if it is not exposed to aggressive air pollution. Many organic substances added to increase waterproofing and make application easier have a detrimental effect on the durability of the rendering.

Products based on a large proportion of Portland cement will imply considerable emissions of the greenhouse gas carbon dioxide during production of the cement. This is reduced in the case of lime-based renders and products with a larger pozzolana content.

Pure plasters produce no problems within a building. Lime and gypsum-based products have good moisture regulating properties. Pure lime plaster can be recycled, in theory, by being re-fired, but this is mostly impracticable in reality. Bricks and concrete blocks rendered with cement plasters are difficult to cleanse for re-use. Lime and cement-based plasters can be classified as inert, so their waste products can be used as fill. Pure lime plaster can be ground up and used to improve the soil. Dumping sulphur and gypsum waste can lead to sulphur pollution, which can be reduced by adding lime.

Lime plaster consists of slaked lime, sand and water. The proportion of lime to sand is 1:3 by volume. The plaster is put on in several layers until it is about 1.5 cm thick. It is most suitable for internal use, such as in bathrooms, but can also be used externally. For exterior use it should be protected against driving rain and continuous damp, otherwise it may be destroyed by frost because of its high porosity.

NEPALESE LIME RENDERING

A plaster from Nepal should guarantee frost-resistance! The mixture consists of 15 kg lime, 6 kg of melted ox tallow and 36 litres of water. The tallow is used as water repellent. The mixture has to be left for 24 hours at a low temperature. The water left on the surface is then poured away, and the creamy mixture at the bottom is mixed with 3 kg of quartz sand. The plaster is applied in layers 3–5 mm thick. Curing takes some weeks, and the surface must be protected during this period (Minke, 1980).

LIME RENDERING ON EARTH WALLS

A condition for the use of lime plaster on earth walls is that the walls must be well dried, and that the surface is even and without cracks. A thin clay gruel is first applied to the wall to give it a rough surface as a key for the lime rendering. The gruel consists of one part clay gruel and two parts sand with a grain size of around 4 mm. Pieces of hacked straw or hay 3 cm long are added and the mixture is then applied in two layers, in quick succession. The first layer is about 2 mm thick and the next is 5 to 8 mm thick. This is then left for two to three days.

The lime plaster is applied in two layers by a trowel, without dampening the surface before application. The first layer consists of one part slaked lime, one part sand with a grain size of 4 mm and three parts hemp fibre or the equivalent. The next layer consists of one part finely sieved lime dough and three parts marble powder. In Japan, where this plaster originates, a small percentage of gelatine from seaweed is added. This makes the surface water repelling, although it is not vapour proof.

For coloured plaster, pigment is added in the second layer (see Table 18.5). The surface is matt from the beginning, but a smooth shiny surface can be achieved by adding a third layer that is only 1 mm thick, consisting of one part finely sieved slaked lime, one part white marble dust and one part pigment. The thin layer of plaster is put on with a trowel and smoothed out until it gels to a lustre finish. Then the surface is polished intensively, preferably with the palm of the hand. The result is of very high quality, but the process is of course very labour intensive.

Hydraulic lime plaster gives a more weather-resistant result than pure lime plaster. It still needs to be applied in several layers to achieve a high durability. The first layer consists of one part hydraulic lime and two parts sand with a grain size of up to 7 mm. The second and the third layers both consist of one part of hydraulic lime and three parts sand with a grain size of up to 5 mm.

Lime cement plaster is used a great deal externally. It is somewhat stronger than lime render and more elastic than pure cement render. From 30 to 50% of the binder is usually cement.

Cement plaster is very widely used as external rendering on retaining walls, tanks, pools, etc. as well as on solid concrete walls, concrete blocks, brickwork, lightweight concrete blocks, etc. First cracks or damage to the surface should be smoothed out with a cement mortar of proportions 1:3. Then the surface should be brushed with a cement gruel of the same mix proportions and, finally, rendered with a cement mortar of 1:1 on concrete walls or 1:3 on concrete block or lightweight block walls. The last treatment can be repeated, giving a surface that is as watertight as possible.

Silicate plaster is based on waterglass as a binder and is an outdoor rendering with good strength, whilst being open to moisture. Small amounts of synthetic polymers are sometimes added.

Gypsum plaster can be used externally, except in areas with harsh climate conditions, but is mainly for internal use, especially as a moisture buffering layer. A mix of one part gypsum to two parts sand is common. This sets in 10 to 30 minutes. For stucco work, a mix of three parts liquid lime and one part gypsum powder is used. More gypsum is needed for relief work in proportions of one part lime and two parts gypsum. A final coating can be one part lime and one part marble dust.

Sulphur plaster can be produced by melting sulphur at temperatures ranging from 120 to 150 °C. Sand, wood flour or the equivalent can be added. It is waterproof but cannot be used on materials with a high lime content.

15.2.4 Flooring

A floor made of concrete reinforced with steel or organic or mineral fibres is highly durable and can cope with both water and chemicals. On the other hand, it is less pleasant to walk on because it is hard and cold. This can be compensated for to a certain degree by adding sawdust, crumbled cork or light expanded clay. A concrete floor can produce a lot of dust through wear and tear unless it is treated with a waterglass solution, oiled, painted with a robust paint or covered by a strong floor covering. If the floor is to be covered with a watertight material, the concrete must be completely dried out before the floor finish is laid, otherwise humidity in the concrete will be trapped inside the construction. This can also lead to an alkaline reaction in the product with possible detrimental emissions to the indoor air. Complete curing of the concrete is best guaranteed if it is well-watered in the period after the concrete work. Gypsum and anhydrite are alternative floor materials with short drying times. They require covering with a strong surface layer. They can sometimes contain polyvinyl-acetate or melamin-urea-formaldehyde adhesives. The class of self-levelling mortars commonly consists of Portland cement, lime and fine sand with synthetic polymers added. The proportion of polymers can be reduced by adding a microfiller of recycled glass.

Terrazzo concrete causes less dust problems than a plain concrete floor, and offers a hard, hygienic surface. A terrazzo floor is a mixture of cement mortar and special chips of crushed hard stone of only a few millimetres in diameter, normally marble or limestone (Figure 15.1). Granite, feldspar or quartz can be used too. The floor is cast in a 15–20 mm-thick layer on top of a concrete underlayer, and the surface is polished to a smooth finish by machine.

15.1

Terrazzo slabs.

Both concrete and terrazzo floor materials are often prefabricated as tiles. These are usually 30 × 30 cm or 40 × 40 cm with a thickness of 4–6 cm.

Concrete floors represent considerable energy use and climate gas emissions during cement production. This is reduced where the cement content is lower. Various additives can also imply production related pollution.

On condition that concrete products are properly cured and treated against dust, they are chemically stable and pose no problems in the finished house. However, steel reinforcement can increase the electromagnetic field in the building.

Concrete and terrazzo tiles can be re-used if they are bedded in a way that makes them easy to remove. They can, for example, be laid in sand and given a weak lime cement mortar joint. Concrete floors cast in situ can at best be broken up and recycled as low quality aggregate or fill.

15.3 STONE SURFACE MATERIALS

Basic info is found in Chapter 7.

Natural stone in the form of slates is well-suited for roofing as well as wall cladding and floors. Tiles, slabs and sheets cut from limestone, marble, syenite, sandstone and granite can be used as a floor finish, and as internal and external wall cladding.

Slate was used for roofing in France as early as the thirteenth century on castles, palaces and churches. The material was later widely used in many parts of Europe, including on homes and more simple buildings. However, the use of slate materials has declined since the beginning of the twentieth century. Seen from an environmental and functional point of view, few materials can compete with slate. In highly exposed areas it can successfully be used for cladding on all exterior surfaces, probably as the most robust alternative. Slates for roofing and cladding are usually cut into small sizes by simple splitting and dividing; slates for floor coverings are most often supplied as squares or rectangles.

Cut and polished stone products have been used increasingly during the twentieth century, especially in public buildings. Most of the stone types used are not strongly layered and, therefore, need a more advanced cutting and production technology than in the processing of slates. Floor tiles of granite, limestone and marble are usually produced in thicknesses of 2 to 3 cm, whilst sandstone may be cut to around 8 to 10 cm thick because of its lower strength. All stones can be polished, which simplifies maintenance.

The occurrence of slates and other stones for tiles is reasonably plentiful and well spread. They are most often extracted from open quarries, with the consequent landscape impacts and possible disturbance of local ground water and biotopes. The energy use in extraction and production processes is initially quite low, but naturally rises the more the stone is cut, worked and polished. Since stone is heavy, the transport energy involved makes it difficult to justify hauling it long distances from its source – which is often the case. Although slate is still fairly widely produced in Europe, cut stone and marble used in Europe today has sometimes been shipped from Asia or South America.

Certain types of stone containing quartz and dust can be a risk during the working of the stone (see Table 7.3). Slate, limestone and marble have negligible radioactivity and are no problem for the indoor climate. Certain types of granite can present a problem as a source of radon gas.

Most stone floors are easily looked after, durable and resistant to water and other liquids. Marble reacts with urine. Stone floors can be hard and cold, unless floor heating is used.

External claddings of limestone can be affected by urban pollution. Unprotected porous sandstones can easily be damaged by heavy rain and frequent freeze-thaw cycles. This could become more serious in Northern and Eastern Europe as a result of climate change.

Slate and stone tiles laid in a weak mortar or fixed mechanically can easily be taken up and re-used. Often over 90% of the slates from an old roof can be re-used, once the few slates damaged by frost, moisture and dismounting have been subtracted. All stone waste can be useful as a rubble fill, or for other purposes, and dumping stone waste is not necessarily an environmental problem unless it is in large quantities.

PRACTICAL USE OF STONE SURFACE MATERIALS

ROOF COVERING

Before the work starts, slate tiles are sorted into two, three or four groups of different thicknesses, unless this has already been done at the quarry. The underlay is usually a timber board roof with bitumen felt. The slates are fixed onto battens, most commonly 25 × 50 mm. The distance between the battens depends upon the type of slate and its dimensions, and is usually decided by the distance between the lower edge of the slate to the fitted nail holes or notches, minus the overlap.

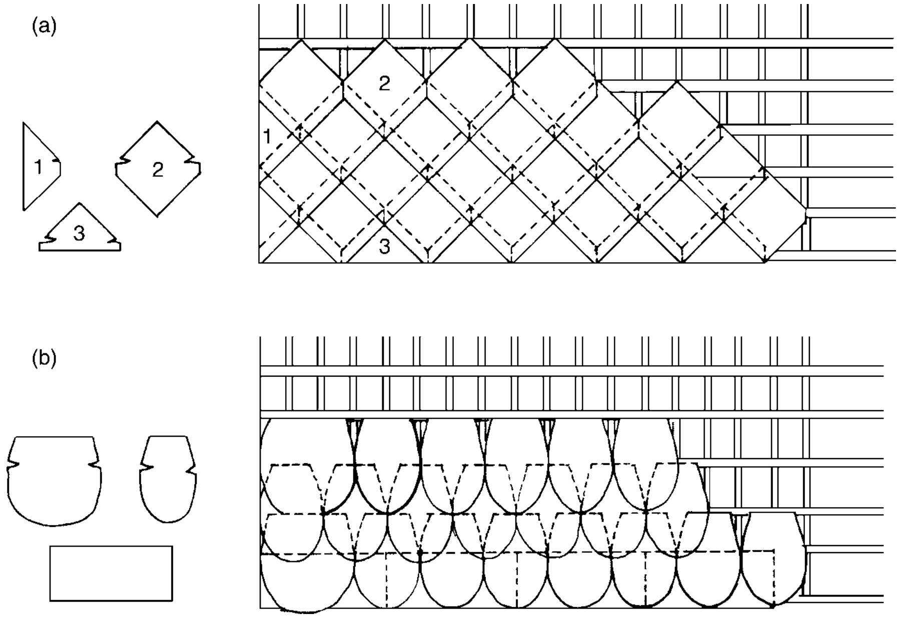
The thickest slate is laid furthest down on the roof, to avoid large variations in thickness on the other courses. A special slate hammer is used to split and shape the tiles, if necessary. The tiles are fixed with special slate nails that are 25/35 mm, 28/45 mm and 28/55 mm according to the thickness of the slates. These are a critical part of the construction and should be of especially high quality. The nails are never hammered in completely; a little slack is left so that the slates can move. If they are nailed tightly they will crack. The ridge is then covered with rectangular slate tiles, timber boarding, zinc, copper or even turf.

Rough tiles. When laying rough tiles, holes are first bored or hacked into the tile with a drill or a special hammer. The tile is fixed to the batten with a strong galvanized nail. For large tiles wooden pegs made of ash or juniper can be used. As rough tiles do not always lie tightly on each other, they can be broken by heavy snow loads. One way of resolving this problem is to put lumps of clay under the end of each tile. If time is spent sorting the tiles so that they fit well together, then a roof of rough tiles can be as waterproof as any other.

Patchwork tiles (Figure 15.2). Patchwork tiles can be laid as a single or double covering. A double covering with a minimum slope of 18° can tackle most climates. With a single layer the slope should be a minimum of 22° in moderate climates and more than 27° in severe climates.

For single laying the tiles must be at least 12 mm thick. For double laying they need only be 6 mm thick. The distance between the battens for double laying is somewhat less than half the length of the tile. An overlap of at least 50 mm is recommended.

Patchwork tiles can also be used on rounded corners, and with some modification on conical, spherical and cylindrical forms. The main rule is that the size of the tile is reduced proportionally with the radius it is to cover. The tiles are nailed directly onto the rough boarding of the roof. To avoid the stone splitting because of the movement of the roof, each tile must be fixed to only one piece of boarding.



15.2
Patterns for laying of (a) square tiles and (b) patchwork tiles.

Square tiles (Figure 15.2). The square tile is used for single-layer roofing. The overlap should be at least 45 mm for small tiles and 75 mm for large tiles.

WALL CLADDING

It is seldom advisable to fix thin stone tiles directly to a wall with mortar. The tiles can easily loosen or be broken. This can happen either through expansion when exposed to the sun, or by the formation of condensation behind the tile that then freezes and pushes it off. If the grain of the tile is vertical, there is a stronger chance of it being knocked off by frost than if the grain is horizontal. Cut stone cladding is therefore usually mounted on special metal anchoring systems, with good ventilation behind the stone. The metal ties should be stainless steel or a copper alloy, and are bored into the structure. This type of cladding is expensive and is most often used on offices or public buildings.

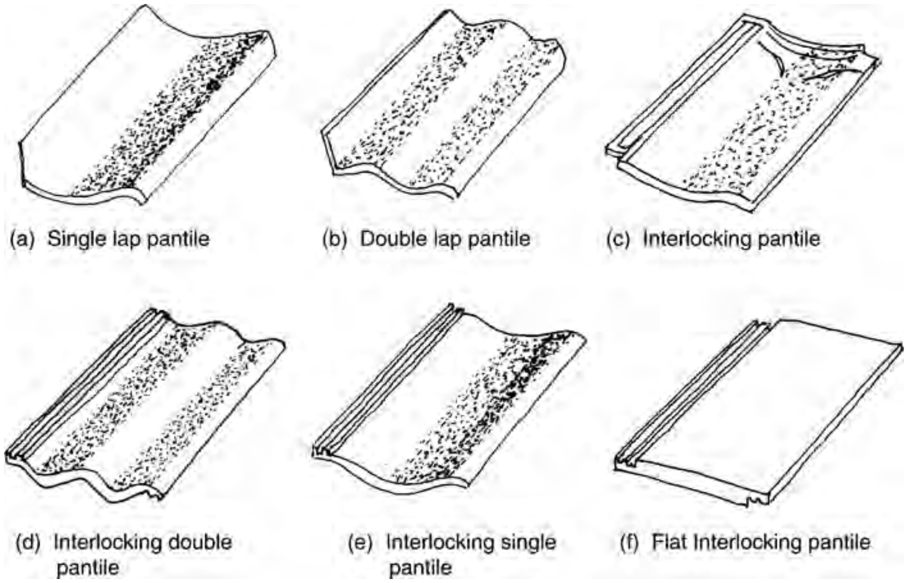
Slates for cladding can be used in the same way as for roofing. Most forms can be used, though patchwork and square tiles are the most appropriate because of their lightness. Only one layer is needed, and is mounted with slate nails, with good ventilation underneath.

FLOOR COVERING

A natural stone floor can be laid in several ways. It is common to lay both cut stone and slate in mortar directly on a concrete base. The concrete is primed with a mix of cement and sand (1:1) while the mortar for laying the tiles is a mixture of cement and sand from 1:3 to 1:4. The mortar is laid to the necessary thickness and before laying the stone tiles are given a coating on the underside with a cement and sand grout (1:1). The tiles are then knocked carefully into place with a rubber hammer. The joints are filled between three and seven days later with a grout of cement and sand (1:3).

For larger floor tiles hard deciduous wood can be used in the joints instead of mortar, or the mortar can be replaced with sand. The possibilities of re-use are then very good.

Marble is the only stone that needs regular maintenance. This is carried out with wax or polish.



15.3

Roof tiles in fired clay (a–c) and concrete (d–f). Non-interlocking tiles require a steeper roof.

15.4 FIRED CLAY

Basic info is found in Chapter 8.

Fired clay products can be used for a wide selection of surface materials for roofs, walls and floors.

Roof tiles of fired clay were used very early in the history of the Mediterranean countries, the most popular being 'nun' and 'monk' tiles. In the mid-nineteenth century, the interlocking tile was first produced in France; compared to previous types, it provides better waterproofing and increased fire safety (Figure 15.3).

Roof tiles require high clay content and low lime content. Fired lime particles can easily absorb moisture in damp weather and destroy the tile. The tile is fired at a temperature approaching sintering, about 1000 °C, to reduce porosity. Roof tiles can be glazed and coloured, mainly for aesthetic reasons.

Clay brick veneering of inner and outer walls is usually done with ordinary construction bricks that are placed in mortar on concrete, steel or timber structures. A special version is the fired clay slab that can be produced in dimensions up to 60 × 180 cm with a thickness of 3–4 cm. It is usually mounted on special metal anchoring systems, with good ventilation behind. Brick products can also be used as flooring, laid on sand or in mortar.

Ceramic tiles are used on floors and walls. These are usually square or rectangular in form, but specially designed tiles of many other shapes (e.g. triangular, octagonal or oval) are also available. Tiles that are coloured right the way through are usually dry pressed and fired to sintering temperature. Many products have an additional glazing.

Fired clay products are based on raw materials found in abundance in most regions. Products destined for use as exterior cladding, roof covering, or untreated floor covering should have a very low porosity rate. As this entails firing at high temperatures, this necessitates a high

15.4
Traditional face cladding with fired clay tiles.

energy demand in the production process and large emissions of the greenhouse gas carbon dioxide, as fossil fuels are most often used. Lime cannot be added to reduce emissions of sulphur, as this would increase the porosity of the products. This is not a problem with brick veneers for inner walls; here, it is also possible to use low-fired products.

Fired clay products are excellent materials for indoor areas. They are hygienic, do not release gases or dust, and are usually good regulators of temperature and moisture, the latter only if they are not highly fired and sintered. Modern jointing materials for ceramic tiles usually have polymers such as epoxy and polyurethane as ingredients. These can give unhealthy emissions into an indoor environment. In Sweden, mastics with organic constituents have led to mould problems, especially in bathrooms. Pure mineral alternatives are better for both floors and walls.

Fired clay products are very durable. They are not susceptible to aggressive gases and pollution in the same way as concrete and natural stones containing lime. To take advantage of the material's durability, the products should be mounted or fixed in such a way that they will be easy to dismantle and recycle. Roof tiles are no problem to re-use, but it must be remembered that tiles in coastal climates have often been exposed to more frequent changes of temperature between freezing and thawing, making them more brittle. A brick floor laid in sand can be lifted and re-used. The same can be said for internal brick cladding that is laid in a lime mortar or clay. If a mortar rich in Portland cement is used, both careful dismantling of the wall as well as removing of the mortar afterwards is practically impossible.

When crushed, fired clay products can be recycled as aggregate for smaller concrete structures, render and mortars. Waste products from plastics-based mortars for jointing and colouring containing heavy metals are problematic. In cases where antimony, nickel, chrome and cadmium compounds are included, special disposal is required. As long as no standardized coding exists for coloured ceramic tiles, all tiles must be treated as a dangerous waste product.

15.5

Floor covering of brick in sand, which are easy to remove and re-use.

RE-USABLE BRICK FLOORING

A brick floor can be laid without cement using all types of bricks or thick tiles (Figure 15.5). Even tiles produced from old bricks (see Figure 13.16) can be used. It is, however, important to choose a brick with a smooth surface.

A 3–5 cm-thick layer of fine sand or rock flour is spread on a firm base and thereafter dampened and lightly compressed. The bricks are knocked into place with a rubber hammer and sand is poured into the joints. A weak cementitious joint-filler can also be used, such as hydraulic lime. The floor is then sprinkled with linseed oil, and this treatment is repeated twice at intervals of one week. After each treatment surplus oil must be wiped off. The linseed oil binds the sand in the joints and makes the brick surface easy to clean. It is also possible to treat just the joints with linseed oil, and treat the bricks with a soft soap.

Re-usable brick flooring can be used in most houses, and is especially appropriate where there is underfloor heating so that this is easily accessible for repair or modification.

CERAMIC TILES IN PURE CEMENT MORTAR

Mortar is made of cement and sand in proportions of 1:4 or 1:5, and water, giving it the consistency of damp earth. It is laid to a thickness of 2.5–3 cm and evened out. A thin cement and sand grout (1:1) is then poured on and spread with a trowel. Maximum grain size for the sand should be 2 mm. The tiles are knocked in with a rubber hammer. After a few days of setting, the joints are filled with a cement and sand grout (1:1–3), the maximum size of grain being 1 mm. After jointing a dry version of the jointing material is spread over the whole surface in a thin layer. This lies in place until the laying pattern of the tiles becomes visible. The surface is then cleaned, and the floor is ready after four days curing.

Wall tiles are mounted in almost the same way with the same mix of cement and sand. It is an advantage if the back of the tile is textured and has a semi-porous surface.

15.5 SURFACES OF EARTH

Basic info is found in Chapter 8.

Earth products can be used for walls and floor surfaces. Their most important quality is that they have a high moisture buffering capacity. They also have good thermal and acoustic properties, and provide a thermal mass that is useful for maintaining stable temperatures in a building.

On wall surfaces earth products are primarily used as renders applied on masonry or concrete. Exterior use of such plasters is not normally recommended in cold climates unless sufficient roof overhang and good surface coating can be assured. Prefabricated blocks and panels for interior wall surfaces are now available in central Europe (Figure 15.6).

These are made of pure, clay rich earth reinforced with natural fibres such as wood shavings or shredded straw. They may be supplied with tongue and groove joints. As panels they are produced in dimensions up to 120 cm and are from 25 to 50 mm thick. Blocks are typically 10 cm thick and strong enough to use for internal partition walls.

Rammed earth floors are probably still the most common floor surface on earth. They are soft and reasonably warm. Prefabricated earth tiles and slabs reinforced with wood shavings can also be found. Their thickness is normally around 50 mm. All jointing is done with clay mortar. Earth floors need special treatment to be sufficiently durable and to avoid dust. There are many traditional techniques for this in different parts of the world. Linseed oil is widely used.

Earth-based surface materials entail minimal environmental impact during extraction, manufacture, use or recycling. The raw materials are abundant, and many types of earth can be used even though some are better than others. Because suitable earth can be found almost everywhere, transport related pollution and climate emissions should be unnecessary; earth is a local building product *par excellence*.

Once installed, earth products contribute positively to the indoor environment. Their durability is high, even if they are not as strong as some industrial materials. They are very flexible for change, repair and dismounting. Earth products can be directly recycled back to the earth.

15.6

Assembling of clay panels.
Source: Claytec.

15.7

Applying loam plaster.
Source: Hock.

LOAM PLASTER

Loam plaster consists mainly of sand and silt with only as much clay as is necessary. Animal hair or cut straw is added as reinforcement. Adding rye flour improves the resistance of the surface against dry and moist abrasion. When the mix sticks to a sliding metal trowel held vertically, yet is easily flicked away, the correct consistency has been reached. The underlying surface has to be sufficiently rough and should be moistened before the work starts. If the surface of the wall needs a layer thicker than 10–15 mm, this should be applied in two or even three layers to avoid shrinkage cracks. To improve surface hardness cow dung, urine or lime should be added in the top layer. To provide resistance against abrasion the surface should be finished with a coat of silicate or lime paint (Minke, 2006) (Figures 15.7 and 15.8).

15.6 BITUMEN-BASED MATERIALS

Basic info is found in Chapter 9.

Rolls of building paper or thicker felt impregnated with bitumen are the most commonly used waterproofing membranes in both the exterior and interior of buildings (see Chapter 14). These are also referred to as ‘tar paper’. In wider rolls this is also a very common, simple roof covering. In felt products, bitumen is mixed with a filler such as limestone or sand and reinforced with a weave of glass fibre or polyester. The products for roof covering are topped with a robust layer of ground stone. The felt is glued and/or pinned to a firm base of wooden panelling, mineral sheeting, etc.

Bitumen is a heavy fraction of fossil oil. The resource base is thus very limited and its use entails heavy pollution and emissions of greenhouse gases, in addition to aromatic hydrocarbons.

15.8

Planing loam plaster.
Source: Hock.

During their lifetime on buildings, a significant amount of bitumen can be washed off and pollute the environment. Their durability is not very high, and bitumen surfaces often have to be renewed every 15 or 25 years. The products cannot usually be re-used or recycled as new materials. Where glued on to underlying surfaces, these too lose their potential for recycling. Normally they must be treated as special waste. If combusted for energy recovery they cause similar emissions to fossil fuels.

15.7 PLASTIC SURFACE MATERIALS

Basic info is found in Chapter 9.

One of the principle advantages of plastics is that they can be made to almost any consistency, durability or shape. Plastic surface materials can be sheets, panels, plaster, terrazzo, soft roof and floor coverings, carpets and wallpapers. The two latter uses are discussed in separate sections at the end of the chapter.

Sheets and panels are usually composite products consisting of cellulose paper combined with plastics, usually a thermosetting plastic containing phenol or melamine (about 25% by weight), pressed together under high pressure and heated. These products are mainly used for internal cladding and flooring. Sheets for exterior use are often of polyester with a mixture of stone particles reinforced with fibreglass.

Synthetic plaster is most often based on acrylic copolymer mixed with crushed limestone, sand, colour pigments and water. Synthetic plasters have a low diffusivity to humidity and should be used with caution on external surfaces.

Traditional *terrazzo flooring* consists of marble or other stone aggregates set in cement mortar. The mortar can be substituted with synthetic glue, usually epoxy resins, making thinner dimensions possible, but introducing environmental disadvantages.

Seamless plastic flooring is applied as liquid and consists of a polymer with fillers of sand, ground stone, colour pigments and often plasticizers like dibutylphthalate (DBP). The recipe can also include nonylphenol. The polymer is most often epoxy, but polymethyl metacrylate and polyurethane are also used.

Soft plastic coverings are widely used flooring materials and are usually produced from polyvinyl chloride (vinyl flooring), polyolephines and synthetic rubbers. Among the latter, the most frequently used is styrene-butadiene rubber (SBR) but also products of butyl rubber (IIR) and ethylene-propylene rubber (EPDM) are available. In the production of vinyl flooring the polyvinyl chloride is mixed with fillers such as sand, chalk, kaolin, wood flour, zinc oxide, lime or powdered stone and recycled glass. Colour pigments, softeners and stabilizers, which can contain lead and cadmium, are also added. The softeners are usually added in quantities between 10 and 20% and most important are dietylhexylphthalate (DEHP), diisononylphthalate (DINP) and benzylbutylphthalate (BBzP). Chlorinated paraffins are also used as so-called secondary plasticizers and at the same time serve as flame retardants. The material is often glued to an underlay of jute, polyester, cork, foamed polyvinyl chloride or fibreglass. Several of the same additives are also a part of products based on styrene-butadiene rubber (SBR) and polyolephines which also quite often include fire retardants. Softeners are, however, not needed in these products. Soft plastic coverings are most often glued to a subfloor of concrete, chipboard, gypsum, etc., usually with an acrylate adhesive or polyvinyl-acetate (PVAC).

Products for roofing are mostly based on polyvinyl chloride, chlorinated polyethylene, ethylene-propylene rubber (EPDM) and polyolephines. The products are composed with much of the same ingredients as in floor coverings and include fire retardants that are often brominated hydrocarbons. Additional treatments for ultraviolet stabilization are necessary. Softeners are needed only in products of polyvinyl chloride.

The main raw material for all plastic products is fossil oils. However, some products are, to a growing extent, based on recycled plastics. The energy use in the production of plastics is high and it entails substantial emissions of carbon dioxide, organic solvents and various other environmental toxins.

In the indoor climate, a wide range of chemical irritants can be emitted (Ehmsperger *et al*., 2006). Very high emissions have been detected from vinyl flooring on concrete because of alkali reactions. The most critical emission from vinyl products, however, will be the phthalates (DEHP, BBzP and DINP) which are emitted as long as the building is used. Each year around 1% of the total amount contained in the product is emitted. There is a clear relationship between the occurrence of DEHP and asthma in children (Øye, 1998; Jaakkola *et al*., 2000). DINP is regarded as less damaging. SBR flooring has been known to emit styrene and butadiene. From products containing polyurethane, emissions of unreacted isocyanates is a significant risk.

Floor coverings of polyvinyl chloride and SBR will shrink somewhat as the softeners evaporate, and damage can occur in the joints which makes them dirt traps and an attractive breeding ground for fungi. On all interior plastic surfaces, the production of bacteria is generally several times greater than on mineral or wooden surfaces with moisture regulating properties.

Glued plastic products are difficult to disassemble in the demolition phase, and re-use is probably not an option for most products. A few of the products can be down-cycled, whilst incineration for energy recovery probably will be preferred for most of them. However, when burning plastics, the emission of carbon dioxide will be the same as when oil is fired. Dioxins are emitted from the burning of polyvinyl chloride. Ash and waste will contain a wide range of pollutants and must be deposited at controlled tips.

15.9

Wood-plastic composite used for cladding, outdoor deck floors, railings and fences.

PANELS OF WOOD-PLASTIC COMPOSITE

Wood-plastic composite is made of recycled plastic including polyethylene, polypropylene, polyvinyl chloride, etc. and wood waste and is used as exterior cladding (Figure 15.9). The wood waste is reduced to sawdust and mixed with the polymer to a dough-like consistency and then extruded or moulded to the desired shape. Colour pigments and ultraviolet stabilizers are often added. The product probably needs less maintenance than wood cladding; at least during the first years, and it does not rot. Wood plastic composites can be regarded as a sensible way to delay the final energy-recycling or dumping of used plastic products.

15.8 LIVING PLANT SURFACES

Basic info is found in Chapter 10.

Exterior surfaces can be protected with living plants. These can be divided into two groups: planted roofs and wall coverings of climbing plants.

Very positive environmental qualities result from the use of plants as living surface treatments. The methods are simple, and the plant and earth resources are infinite and can be used directly from their source. The potential negative environmental aspects are small. A caveat, however, is the need for waterproofing under a planted roof, which must be either a bituminous product or plastics-based on polyvinyl chloride, polyethylene or ethylene-propylene rubber (EPDM). Trelliswork for wall coverings impregnated with toxic substances will have a negative environmental impact.

Earth in itself has unlimited durability; it is mainly the waterproofing layer that decides the life of a green roof. Leakage problems and damage usually arise around flashings, where pipes, chimneys, etc. penetrate the roof. For plant claddings the durability of the trelliswork is critical.

Earth removed from roofs returns to the soil. Waterproofing layers of plastics can, in theory, be cleaned and recycled, but this is seldom done in practice. Impregnated trelliswork must be deposited at special tips. Bituminous materials, plastics and impregnated wood can be recycled for energy. When burning plastics and bitumen, the emissions of carbon dioxide will be the same as with fossil fuels. From the burning of products of polyvinyl chloride dioxins will be emitted. Ash must be deposited at special tips.

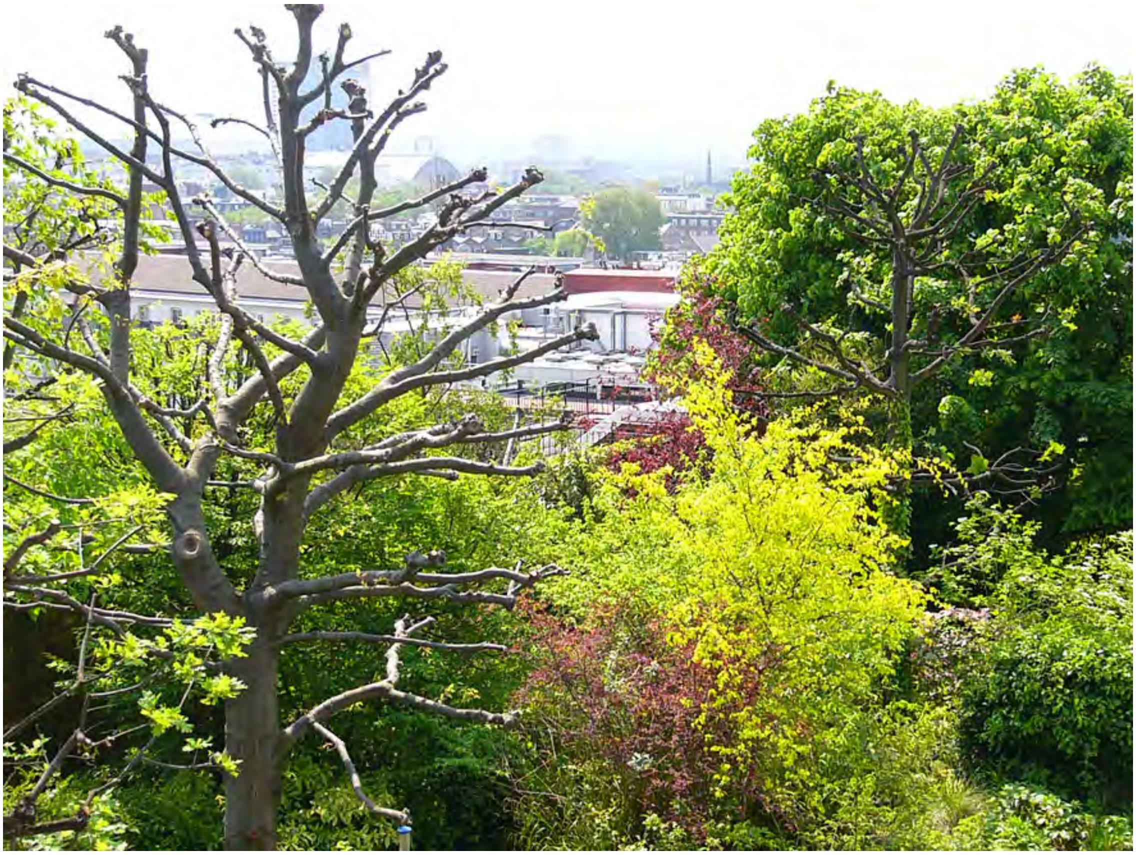
ENVIRONMENTAL ADVANCES WITH PLANT SURFACES

For the town. Plant surfaces are an important factor in the environment of towns. Green plants bind and break down gases such as nitrogen oxide, carbon dioxide and carbon monoxide and produce oxygen. A combined leaf surface of 150 m^2 produces the oxygen needed for one person. A 150 m^2 roof that has a 100 m^2 leaf surface per square metre thus provides for the equivalent of 100 people. A wild, overgrown grass roof produces about 20 times as much oxygen as a well manicured lawn.

Planted surfaces bind dust. A city street without trees has approximately 10 times more circulating dust in the air. Planted surfaces also reduce vertical air movement. Over a conventional roof, vertical air currents of up to 0.5 m/s can be caused by solar heating of the roof material. On metal roofs the temperature can be as high as 100 °C. This air movement can pick up dirt and form clouds of dust over towns. A turf roof will normally reach no more than 30 °C, almost totally eliminating the rising air movement (Figure 15.10).

Planted roofs also function as retention basins, in order to delay the release of storm water that overloads many urban drainage systems. When rainwater passes through a green roof, particulates can also be filtered out of the water. This can reduce pollution downstream.

For the house. Planted surfaces can often provide good thermal insulation since pockets of still air are formed between the plants giving the same effect as a fluffy fur coat. Plants also reduce the effects of wind infiltration into the underlayer. For a large part of the year, a planted surface acts as a solar panel: turf roofs have a particularly high absorption coefficient.



15.11

The roof garden of a large department store from early 20th century in South Kensington, London.

The plants also develop their own warmth during the cold part of the year and thus prevent freezing. During the summer, dew will form on the roof in the morning. For every litre that condenses, an amount of warmth the equivalent of 0.65 kWh is emitted.

The damp earth in the turf roof has a large capacity to store warmth. This can give the building a stable, warm indoor climate during the winter and a cooler indoor climate in the summer. Walls covered in plants are also cooled by their shade during the summer.

A turf roof gives a sound reduction effect of 46 dbA with a 20-cm thickness of the earth layer and about 40 dBA with a 12-cm thickness. This kind of roof is therefore particularly suitable along highways and near airports.

15.8.1 Planted roofs

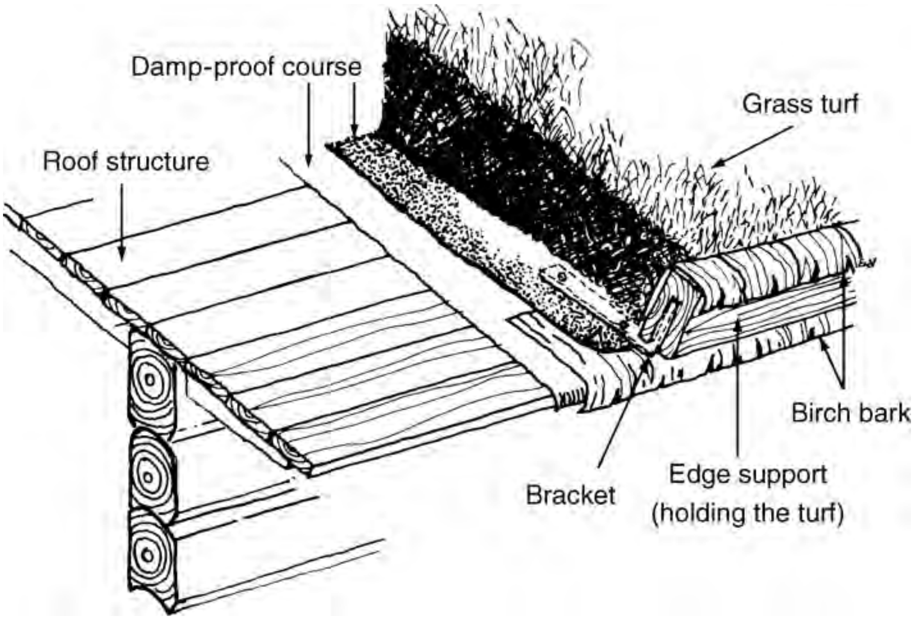
Turf roofs have featured in the history of building in Northern Europe as long as can be remembered. Resources have been boundless and laying methods relatively simple, though labour-intensive. The high thermal insulation offered by turf roofing made it a strong competitor against slate, tiles and other materials that have subsequently appeared. The thermal insulation makes it popular even in the tropics; there are houses in Tanzania that have a 40 cm-thick layer of earth with grass on the roof. During the last 20 years there has been a renewed interest in green roofing, especially in heavily polluted towns in central Europe, such as Berlin.

Green roofs are usually associated with folk architecture, with only grass species growing. But many other plants can be chosen, even bushes and trees. The roofs do not necessarily have to be sloping but can be almost flat. However, flat roofs should always have a slight gradient to enable drainage.

The roofs are made up of several layers (Figure 15.12). Topmost are the plants with a soil layer underneath. Under this is a filtering layer which prevents earth from falling through, and beneath this is a further layer for draining away excess water. The waterproofing layer is furthest down and must be robust enough to prevent roots from penetrating and water entering the structure. On a sloping roof of over 15°, the filtering or draining layers are unnecessary, but otherwise the roof is built up in the same way (Figure 15.13).

The plant layer. A wide spectrum of plants can be grown on roofs, some of which strengthen the network of roots and thereby the roof itself. They can stabilize it, retain moisture over a dry period and even reduce fire risk. There are evidently many advantages to a varied flora on the roof (see page 163).

The earth layer (Table 15.4). The usual turf for a roof comprises grass that is well bound by its roots, cut up into pieces 30 × 30 cm and about 10 × 15 cm thick. In Norway it is traditional practice to use two layers of turf, the lower layer turned with the roots upwards, the upper with the grass on top. On the ridge, longer pieces of turf are used. Even loose earth can form a top layer, compressed to the same thickness as the turf. On a sloping roof, it is advantageous to lay wire netting with 2–3 cm of earth on it before compressing the earth and sowing. For a roof with a slope of more than 27° it is necessary to lay assisting structures of battens to hold the turf in place. These are not fixed through the roof covering but at the ridge, to each other, or resting on the eaves of the



15.13

Principles for using turf coverings on a sloping roof.

Source: Norwegian Building Research Institute.

Table 15.4 *Required depth of soil for various vegetation*

Plants	*Minimum depth of earth*	*Type of roof*
Grass	10 cm	Flat/pitched
Bushes	25 cm	Flat/low pitched
Small trees	45–80 cm	Flat/low pitched
Vegetables	45–60 cm	Flat

roof. The structures do not have to be of a very durable material, as they lose their function when the system of roots binds together.

The earth should have plenty of humus, which can be increased by mixing in compost or peat. A depth of at least 15 cm of earth is recommended. A thinner layer will dry out or erode easily. For *sedum* species, which are particularly resistant to dry periods, the depth of earth need only be 6 cm. On a roof with not much of a slope or a flat roof it is possible to use a layer of earth without turf for growing vegetables.

In Berlin around the turn of the century, a method of covering roof gardens with 20 cm building waste mixed with earth was used. It was partly introduced to prevent the spread of town fires. A whole series of such courtyards still exist in the quarter of Neu-Köln.

The filter layer, which is necessary on a roof with a slope of less than 15 °C, can be rough sand or sawdust.

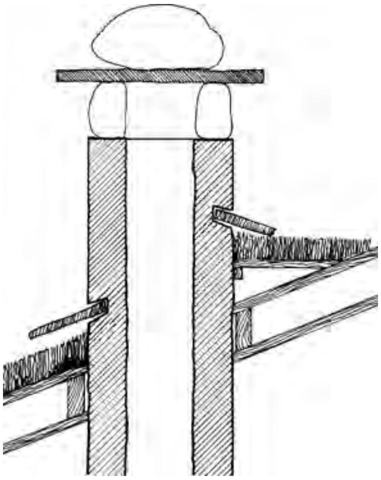
The draining layer, needed on a flat roof, can be rough or fine shingle or loose expanded clay pellets.

The waterproofing layer is necessary to ensure that excess water runs off the roof. There are different ways of achieving this, but the most common is bituminous or plastic-based solutions (Table 15.5). Steel, aluminium and cementitious sheeting has a limited usability since they are most often eaten away by the acidic humus.

Flashing around chimneys and pipes that go through the roof are usually of lead or copper. The use of these materials should be kept

Table 15.5 *Alternatives for waterproofing of turf roofs*

Material	*Amount of work*	*Lifespan*	*Areas of use*
Steel/aluminium sheeting	Low	Short	Sloping more than 15°
Corrugated cement sheeting	Low	Medium	Sloping more than 15°
Bentonite clay with bituminous felt	Low	Unknown	Flat roofs
Slate/tile roof	Medium	Long	Sloping more than 20°
Bituminous felt	Low	Medium/low	All roofs
Polethylene sheeting with bituminous felt	Low	Unknown	Sloping more than 15°
Polyvinyl chloride sheeting with bituminous felt	Low	Unknown	All roofs
Bark from birch	High	Long (30–100 years)	Sloping more than 22°



15.14

Slates for rain protection around chimneys.

to a minimum for environmental reasons. Slates can be used around chimneys on pitched turf roofs (see Figure 15.14).

MATERIALS FOR WATERPROOFING OF GREEN ROOFS

Birch bark was the most commonly used waterproofing material for turf roofs until the mid-twentieth century. It is laid in six to 16 layers with the outside facing upwards, and the fibres following the fall of the roof to carry the water towards the eaves. The more layers there are, the better the durability.

The layer of turf over the bark layers must be at least 15 cm deep to prevent the bark from drying out and splitting. A roof angle of 22° is the lowest possible slant for this sort of waterproofing. Using birch bark for waterproofing is a very labour-intensive technique and is dependent upon a limited resource.

Marsh-prairie grass laid on thin branches was the usual waterproofing layer used by immigrants in the drier areas of the USA.

Tar and bituminous products have also been used, to a certain extent. In Germany, a building with a flat concrete roof was constructed in the 1930s. It was coated with coal tar and then a 10–20 cm-deep layer of earth was laid on top. The roof has lasted through the years (Minke, 1980). Coal tar is not particularly good environmentally because of its high content of polycyclic aromatic hydrocarbons (PAH). Using a pure bituminous solution might be better, but there is little evidence as to how durable this would be. If using bituminous felt there should be at least three layers, although durability is probably relatively low because of the acidic activity of the humus in the earth. Polyester reinforced bituminous felt is often used as an underlay for other plastic membranes. The material does not then come into direct contact with the earth.

Plastic. There are many different plastic products on the market for this particular function. The best product from an ecological perspective is polyethylene sheeting of about a 0.5–0.7 mm thickness. This is an oil-based product but is relatively pollution free when in use. When burnt it does not emit toxic gases. The polythene sheeting available today is mainly for sloping roofs. It has studs or small protrusions on its surface that stop the turf from sliding down, and is claimed to be resistant to humus acids. As the plastic is underneath earth, it is not affected by ultraviolet radiation or large changes of temperature, which have a tendency to break down plastics. The durability is unknown as there are no examples that have been in use for a long period. On flat roofs, reinforced polyvinyl chloride sheeting is the most common material. A membrane of ethylene-propylene rubber (EPDM), often blended with polypropylene, can also be used.

Bentonite is a clay containing montmorillonite. It expands in contact with water to become a tough and clay-like mass that prevents water penetration (see page 262). This material is used in tunnel building and can also be used under a turf roof. The depth of earth must then be at least 40 cm to give the clay enough pressure to work against. However, this method is restricted for use on larger buildings with flat roofs. It would still need a layer of watertight polyethylene or bituminous felt underneath. A concrete surface can be primed with liquid bitumen.

CLIMATIC CONDITIONS AFFECTING GREEN ROOFS

Sun. Strong solar radiation can cause the planted surface to dry out too rapidly, especially if it is on a relatively steep roof facing south. In drier climates, roofs with an angle more than 20° need to be shaded or supplied with a thicker layer of earth to give a higher water and heat capacity.

Wind. The impact of wind depends upon the height and shape of the building and local wind conditions; the stronger the wind, the slower the plant growth. Wind also has a cooling effect and can increase the drying rate, even causing physical damage in certain situations. For very exposed areas, plants should surround the building to protect it, with a thicker layer of earth on the roof, mixed with stones to give the roots a better hold.

Rainfall. Even if the earth can, in certain cases, be waterlogged, water is something the planted roof needs in very large quantities. As there is no ground water reserve for them to draw on during a dry period, they are totally dependent upon the storage capacity of the layer of earth on the roof. A short dry period is no problem; after a little rain the plants can quickly recover. Shading can reduce solar penetration and a thicker layer of earth can store more water, especially if it contains more clay than sand. Solutions might include an automatic watering system, especially if vegetables are to be grown. Grey drainage water from the household can be used for extra fertilization.

Pollution. Green roofs have a very positive effect on air pollution, but they can also be damaged by it. This will only occur in situations of extreme pollution where there are strong concentrations of ozone, or dust that settles on the leaves and prevents photosynthesis. If the earth becomes too acid, lime can be added.

Erosion. Green roofs do not receive any nutrition from the natural nutritional cycle, but are constantly losing humus, minerals, salts, etc., as these are washed out. Much can be gained by starting with a rich earth. A little compost can be added occasionally, and autumn leaves should be left lying. The correct mix of plants can also add to the richness of the earth.

15.8.2 Wall cladding with plants

The environmental qualities achieved by cladding walls with plants are somewhat similar to those of a planted roof, with increased wind and rain protection, extra thermal insulation and sound insulation, and better air quality.

There is a certain amount of scepticism as far as plant-clad walls are concerned, based on two main points: (1) that plants, especially ivy, eat into the wall, and (2) that leaves can house all sorts of insects which get into the building. Problems with insects have proven to be almost non-existent. And as long as the material used in the building construction are mineral, such as brick, and the render is of a high quality, then little damage will be caused by plants. In fact, they have the opposite affect, protecting the render from driving rain, drying out and large fluctuations in temperature, etc. In Germany, rendered walls with plant cladding have lasted up to 100 years, whilst normal buildings have been re-rendered three to four times during the same period (Doernach, 1981).

Walls clad in timber panelling and other organic materials are less suitable for plants but, if used, there must be plenty of ventilation between the plant cover and the wall. Ivy and other climbers that can extend their roots into such materials should not be used.

Climbing plants need a little fertilizer; the sun does the rest. The lifespan of these planted surfaces can be as much as 100 years, and ivy has been known to grow on a building for 300 years.

15.15
Wall covering with plants in Budapest.

Orientation and planting

The different façades of a building offer different growing conditions for plants, just as plants can have different uses on different façades depending upon their orientation. Plants that lose their leaves during winter should be grown on the *south side* to take advantage of solar radiation during the winter. In milder climates, climbing fruits or vegetables such as grapes or tomatoes can be grown here. On the *east* or *west side* it is better to have evergreens that form a thick green layer. Deciduous plants can be used if they have a dense growth of branches or a hedge formation. It is best to have a thick layer of evergreen vegetation that is not dependent on sunshine growing on the *north side* (see some of the plant species in Table 10.7).

Planting has to be done during spring or autumn. The plants can be either bought or collected from the wild (e.g. honeysuckle, ivy, hops and blackberries). Most will need to be planted at intervals of 30–50 cm and about 15 cm from the wall. The roots must have space to grow out from the building. Certain climbing plants are sensitive to high earth temperatures and prefer a shady root zone, which can be achieved by planting grass or small plants over them.

Apart from hedges and hanging plants, assistance is needed to help other plants grow. Self-supporting climbers can manage with the help of a rough plaster, while others need more permanent trelliswork. This can be a galvanized steel framework or high quality timber. Timber battens are best placed diagonally. For fast growing plants with dense foliage, extra watering and fertilizing will be needed, especially in the first couple of years. Some plants must be pruned regularly.

15.8.3 Indoor plants

Russian and American space scientists have been working for years with so-called 'biological air cleaners' for use in space ships. These are plants with a high absorption capacity for organic gaseous pollution that is normal in modern interiors, such as vapour from organic solvents and formaldehyde.

Larger plants that do this are ivy (*Hedera helix*), the fig plant (*Ficus pumila*), devil's ivy (*Scindapsus aureus*) and the tri-leaf philodendron (*Philodendron spp.*). Some potted plants such as the peace lily (*Spathiphyllum*) and the spider plant (*Chlorophytum comosum*) do the same. The air cleaning properties vary, and are also dependent upon the leaf area (see Figure 15.17 and Table 15.6).

15.9 TIMBER SHEET MATERIALS

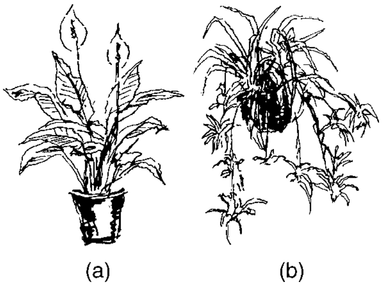
Basic info is found in Chapter 10.

Timber products can be used anywhere in a building where surfaces need to be covered; as whole timber, as an ingredient in laminates and composites for sheeting, as natural rubber flooring or as cellulose for wallpapering (wallpapering is discussed in a separate section at the end of the chapter).

Whole timber can be used to cover roofs as shakes, shingles or planks (Table 15.7). As cladding it can be used as panelling or wattle,

15.16

Plants used for air cleaning in a combined office and apartment building in Nürnberg (Germany). Architect: Joachim Eble, 1997. Photo: Dag Roalkvam.



(a) (b)

15.17

Potted plants with air cleaning properties: (a) peace lily and (b) spider plant.

and as flooring it can be used as planks, parquet or timber cubes. Sheets and boards are produced in forms including fibreboard, cork, chipboard and veneer. The first two of these have their own glue in the raw material which allows them to form the boards; the latter two need added glue. Today these synthetic adhesives are usually based on formaldehyde, polyurethane or phenols added in a proportion of 2–12% by weight. Laminated products are also made with chipboard in the middle and have a veneer surface; or a different type of plastic coating, sometimes finished to look like timber. Natural rubber flooring is a product made from latex extracted from the rubber tree (*Ficus elastica*) with added fillers, stabilizers, colour pigments, etc.

All types of timber, both softwood and hardwood, are used with few exceptions. Products made of chipboard have no particular requirements and can even be made from minced demolition timber. The substances used for glue in the production process and the impregnation materials used in external timber cladding can come from questionable sources (see Chapters 17 and 19).

Timber is often a local resource, and all surface materials made of whole timber can be made locally. Timber is treated best at small mills. It is clear that timber needs human attention, and there are limits as to how mechanized sawmills should be. In whole timber products, 50 to 60% of the trunk is normally utilized, while in particle boards and fibreboards this is often more than 95%.

The energy consumption in production varies from product to product, but is generally low to moderate, with the exception of complicated composites rich in plastics, and some fibre-boards that need a high temperature drying process. The amount of energy needed in the production of natural rubber flooring is about half of the equivalent synthetic rubber products.

Since trees bind carbon dioxide from the atmosphere, all wood-based products store carbon in the finished buildings and for as long as they last. This represents a useful buffer against global warming.

There are generally few environmental problems relating to the production processes at sawmills or joinery shops. Wood dust can, however, be carcinogenic; this is particularly the case for oak and beech. Synthetic glues and impregnation liquids can pollute the working environment as well as the immediate natural environment, as effluent in either water or air.

Table 15.6 *The absorbtion of formaldehyde CH_2O by different plants with a total leaf area of 0.5 m^2 during a day and a night (24 hours)*

Species	*Absorbtion (10^{-3} μg/24 h)*
Banana (*Musa*)	57
Ivy (*Hedera helix*)	48
Tri-leaf philodendron (*Philodendron spp*)	23
Spider plant (*Chlorophytum comosum*)	19
Devil's ivy (*Scindapsus aurea*)	16

(Source: Trädgård, 1989)

Table 15.7 *The use of solid timber as surface materials*

Species	*Roofing*	*External cladding*	*Internal cladding*	*Flooring*
Alder			x	
Ash			x	x
Aspen	(x)	x	x	x[1]
Beech			x	x
Birch			x	x
Elm				x
Juniper		x		
Larch	(x)	x	(x)	x
Lime			x	
Maple				x
Oak	(x)	(x)	(x)	x
Spruce		x	x	(x)[2]
Scots pine	x	x	x	x

Notes: x: Primary use; (x): Secondary use.

[1] Not so hard-wearing, but soft and warm.

[2] Increased wearing when painted or varnished.

Timber is generally favourable in the indoor environment, having good moisture-buffering properties, but these are often eliminated by treatment with synthetic varnishes or vapour-proof paints. Untreated timber has good hygienic qualities. It proves to have far less bacterial growth on its surface than the equivalent plastic surface.

Softwoods can release small amounts of natural formaldehyde for some time after installation, but this is not known to cause problems for people with allergies (Englund, 1997). Cedar contains thujaplicines which are known allergens and should not be used internally.

Glued products can emit a wide range of gases into the indoor air. Glues of polyurethane (PU) and methylene diphenyl diisocyanate (MDI) can emit small quantities of isocyanates; while glues of urea-formaldehyde (UF) emit formaldehyde. Emissions increase with temperature and humidity. UF glues have little resistance to moisture and – if they become damp during transport, on site or when painted with a water-based paint – the boards will give off much higher emissions than a factory dry board. Cork products coated with polyvinyl chloride can emit volatile compounds associated with polyvinyl chloride.

Timber impregnated with heavy metals or creosote should not be used in greenhouses or on roofs, where rainwater passing over the timber runs into soil for cultivating food. Handling of creosote impregnated materials can cause eczema on the hands and feet even without direct contact. Bare skin has to be protected. Creosote can also damage the eyes, and cause more serious damage to health.

Durability is dependent upon the climate, the quality of the material and the workmanship, but is generally good as long as the timber is not overexposed to moisture (see Table 10.9). However, artificially fertilized and quickly grown timber is less durable. Timber roofing is not suitable for damp climates with large variations in temperature. As a result of expected climate changes, the risk of damage will probably increase in Northern and Eastern Europe during the present century.

Technically, all sheeting and boarding can be re-used when fixed in such a way that removal is simple. In practice, this is more viable with internal cladding. Exterior timber boarding panels or timber roofs are exposed to the elements and get worn out over the years, so there is often little left of value. There is also little potential for re-using wood-based boards, with the exception of carefully mounted high quality fibreboard and plywood. In theory, many of the more worn products can be ground for new production of particle board.

Solid timber and fibreboard that is untreated, or treated only with natural products such as linseed oil, can be burnt for energy recovery in normal boilers or composted. Glued products and products laminated with plastic materials have to be treated as special waste and incinerated in boilers with special filters. Impregnated products must be incinerated at especially high temperatures; and is often transported to cement factories where the oven temperatures are sufficiently high to break down most of the toxic compounds. This often implies long transport distances and is, from a purely energetic point of view, probably not worthwhile. Combustion residues must be specially taken care of. All wood waste, even though natural, can lead to an increase in the nutrient level of the water seeping from the tip.

15.9.1 Roof covering

Pine, oak, aspen and larch can be used as roofing. Roofs can either be covered with cleft logs or planks, or with smaller units such as shingles. All timber roofing methods have one common requirement: they must prevent water standing anywhere as this could lead to fungal attack. This requires reasonably steep roofs (the steeper the better) and timber that has a mature quality, rather than fast grown timber. It may even be necessary to impregnate the timber (Table 15.8).

The weight of a timber roof covering varies from 25–40 kg/m^2 according to how the roof is laid and the type of timber. The insulation value varies slightly for the different types of timber, but is generally of no consequence. The use of timber roofs is often limited to small buildings in the countryside. This is because of the high risk of fire, especially when the roof is additionally treated with wood tar. Thick materials usually have better fire resistance than thin materials.

Any form of roofing has to be ventilated underneath. On non-insulated inland outbuildings, the roof covering can be laid directly onto battens fixed to the roof trusses. On housing and in areas exposed to hard weather it is necessary to have a good roofing felt under the battens and a double batten system to allow water to run down under the battens carrying the timber roofing.

It is to the timber's advantage if the roof surface is regularly treated with linseed oil or wood tar, preferably from beech, which has a lower content of aromatic hydrocarbons. An important reason for treating the wood is to increase elasticity and thus avoid cracking. Smaller timber

Table 15.8 *Longevity of timber roof coverings under favourable conditions in a dry and cold climate*

Type	*Lifespan (years)*
Shakes, untreated on steep roof	More than 100 years
Shakes, maintained with wood tar, steep roof	More than 200
Shakes, maintained with wood tar, low pitched roof	More than 100
Cleft log roof, untreated	Probably very high
Plank roof, maintained with wood tar or linseed oil	30–50
Plank roof, pressure impregnated with metal salts	60–80

components, such as shingles and shakes, can be put into a linseed oil bath and warmed to a maximum temperature of 70 °C. In certain coastal areas, cod liver oil has been used.

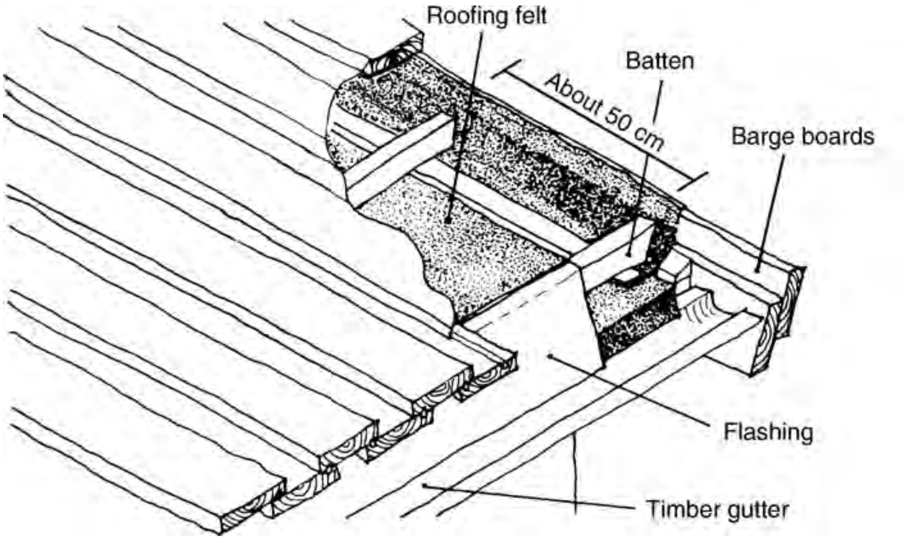
Liquids for impregnation based on toxic mineral salts or oil and coal-based products (see Table 19.3), can be washed from roofs into local ground water and soil.

TYPES OF WOODEN ROOFING

The cleft log roof consists of trunks cleft in half and laid over each other (Figure 15.18). This type of roof is widespread in Finland and Sweden. Cleaving the timber gives a much better water-resistant surface than sawing (see 'Splitting', page 170). The cleft log roof therefore has a longer lifespan than others, as long as the slope is adequate. The bottom layer is often made of planks instead of half-rounded timber and is therefore easier to lay, but this reduces the durability.

15.18

Cleft log roof.



15.19

Plank roof.

Source: Norwegian Building Research Institute.

The plank roof consists of planks in two layers overlapping each other and running down the slope of the roof (Figure 15.19). The plank roof is often also used as a base for other roof coverings.

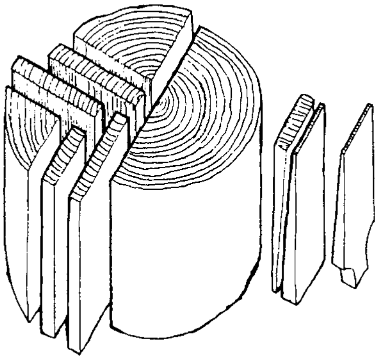
High quality pine should be used in widths less than 15 cm to reduce the chance of cracks forming. There should be grooves on the edges of the upper (pointing downwards) and lower planks (pointing upwards) for draining water. The planks are laid so that they press against each other when they swell in damp weather. The face with the inner grain of the tree must face upwards, especially in the case of the top planks. The part of the plank closest to the base of the tree has the best quality and should be on the lower part of the roof.

The plank roof can also be laid with horizontal boarding. This can only be used for steep roofs and is occasionally found on small towers or ecclesiastical buildings. It was often used on the oldest stave churches. The boarding is nailed with about 5 cm overlap, the inner grain facing upwards.

Shakes. Timber that is to be used as shakes has to come from mature trees and be well grown without any through knots. The trunk is first sawn into 30 to 65 cm long sections and then split into quarters (Figure 15.20). The pith is scraped away. The pieces are often boiled to reduce the chance of cracking when being cleft, but heating to over 70 °C also makes the resin melts out, and impregnating effect is lost.

Cleaving is then performed using a special knife which is 35 cm long and has a handle on each end. The sharp blade is usually placed radially on the end of the log and knocked in. The shakes should be from 1 to 3 cm thick. It is also possible to cleave shakes by machine.

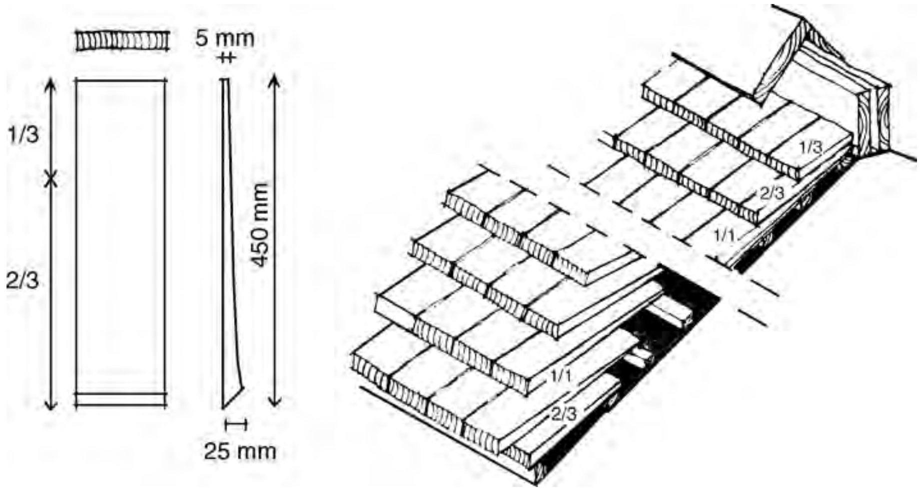
The shakes are fixed on battens using the feather boarding principle with 2–3 mm between them to allow for shrinkage and expansion. A normal covering consists of two or three layers. They are nailed with wire staples so that the holes are covered by the next layer. Usually one staple per shake is enough. The staple should not be so long that it penetrates the roofing felt. Laying details are shown in Figure 15.21. The shakes can be shaped in many different ways, the most complex often being reserved for ecclesiastical buildings.



15.20

System for cleaving softwood shakes. Oak shakes are always cleft radially in the wood.

Source: Vreim, 1941.



15.21

Traditional technique for laying shakes in three layers.
Source: Eriksen.

Shingles are sawn by a circular saw. They are 40 cm long and 10 to 12 cm wide with a thickness of 1 cm at the lower end and 0.5 cm at the upper end. They are laid next to each other with a spacing of about 2 mm, usually in three layers, which means that the distance between the battens is about 13 cm. In the nineteenth century the majority of buildings in New York were roofed with shingles.

15.22

A less processed version of shakes laid in three layers with overlap sideways.

15.9.2 Timber cladding

Timber panelling has a long tradition as a cladding material, first as external wall panelling and later as internal wall and ceiling cladding. The different types of cladding have changed slightly through the twentieth century, particularly to suit mechanized production. Special panelling can include cladding with shingles and shakes. Cladding with twigs and branches also has a long tradition in certain countries. Juniper is widely used and gives functional, long-lasting weather protection.

Panelling for external walls should preferably be of high quality timber. The planks should be sorted on site and the best ones placed on the most exposed parts of the building. Nailing through two planks should be avoided; they may split through differential movement. External cladding should be nailed at an upward angle to avoid water seeping in and settling.

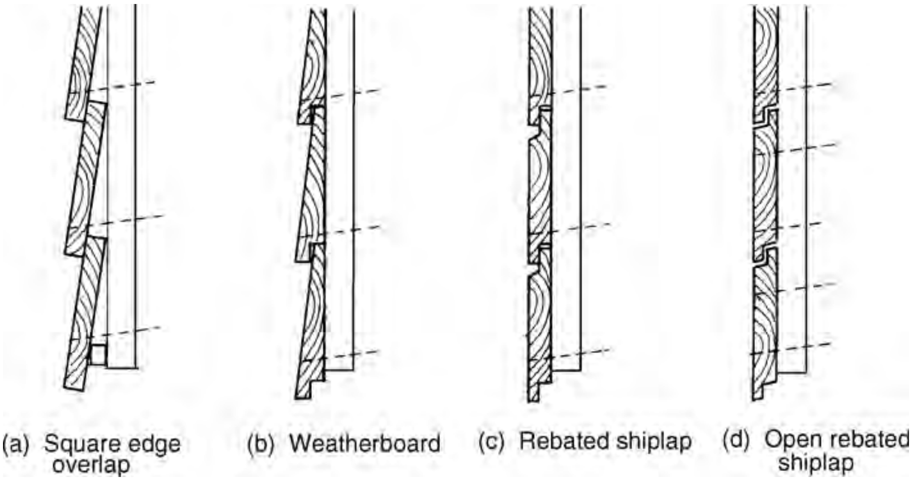
Timber panelling on an external wall is usually far more durable than the equivalent panelling on a roof. It is still important to choose the right system of panelling and use the correct form of chemical or 'constructive' timber treatment (see Chapter 19). A solution of waterglass (see page 90), can be used as a flame retardant.

Interior wooden cladding has a very resilient finish compared with many alternatives, and the surface has good moisture buffering properties if untreated, or treated with surface finishes such as soap or lye.

TYPES OF WOODEN CLADDING

Exterior horizontal panelling is the best choice in exposed coastal areas (Figure 15.23). Driving rain runs off more easily and has difficulty getting behind the panelling. The boards should be cut so that the stronger heartwood is facing outwards. When mounting the panelling, the best quality boarding should be furthest down, where the panels are exposed to most water and to splashing from the ground.

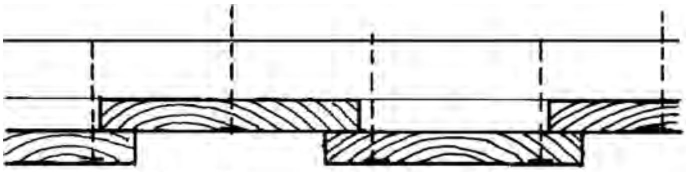
Exterior vertical panelling. Driving rain can penetrate vertical cladding easily so this type of cladding is more suited to inland buildings. It is an advantage to have the



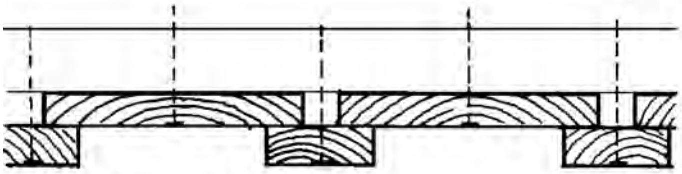
15.23

Horizontal panelling. Type (b) and (c) are less well ventilated sideways and should not be used in wet and windy locations.

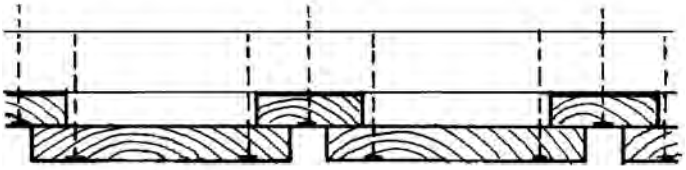
Source: Norwegian Building Research Institute, 2000.



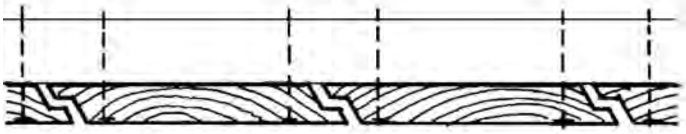
(a) Board on board



(b) Batten on board



(c) Board on batten



(d) Open profiled boarding

15.24

Vertical panelling. Type (d) is less suited in wet and windy locations.
Source: Norwegian Building Research Institute, 2000.

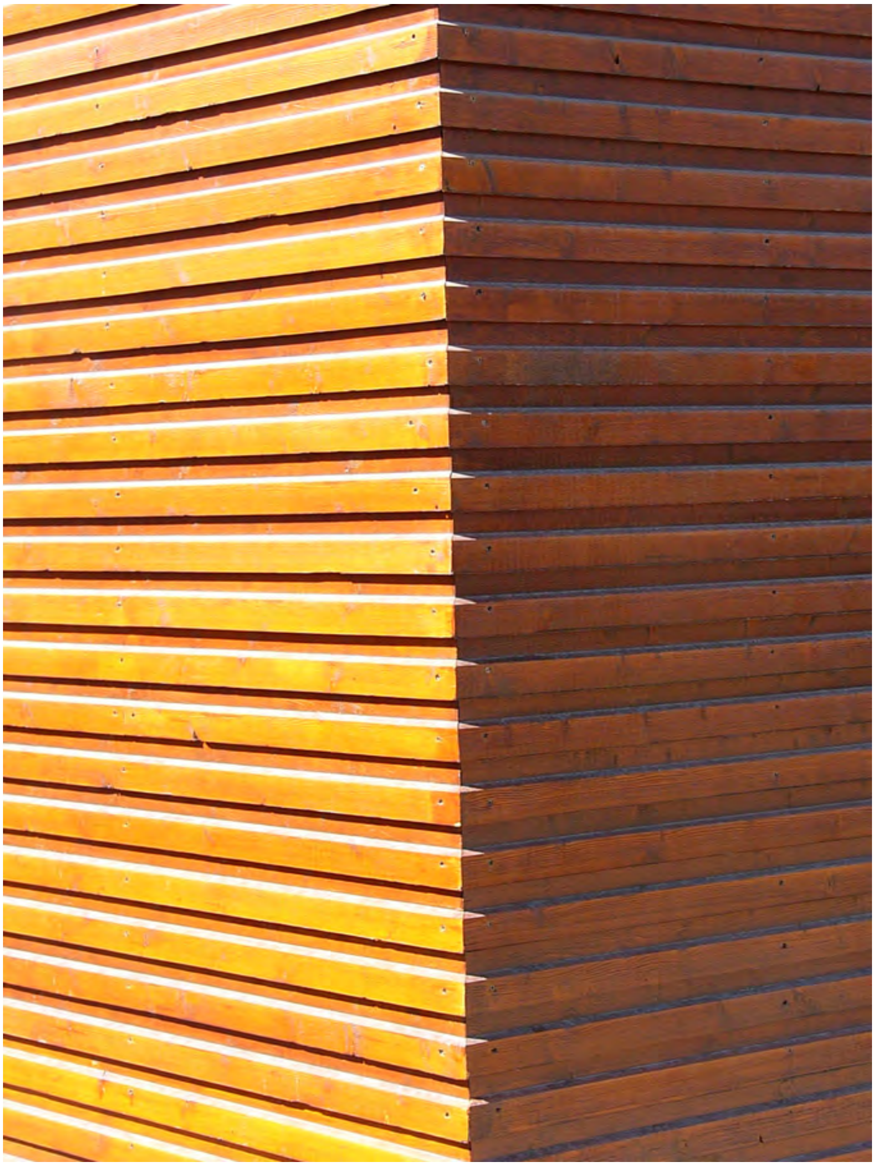
heart side facing the outside in all exterior panelling. It is also a good principle to lay the boarding the same way as it has grown, because the root end has the most heartwood (Figure 15.24).

Exterior diagonal panelling is popular on the continent, especially in central and Eastern Europe, because cut-off ends of boarding and shorter pieces of board can be used. In very harsh climates, diagonal panelling should not be used, since water does not run off as well as from other types of panelling.

Interior panelling. The strength of timber is not so critical for internal use. Quickly grown timber serves most purposes. Softwoods are most commonly used, both as spruce and pine. Hardwoods can also be used. Birch is quite abrasion proof; aspen has a soft surface and a relatively good insulation value, and is often used in saunas. Because of its lasting light colour, it is also attractive as a ceiling. Other hardwoods appropriate for interior panelling are oak, ash, elm, lime and alder. Alder is particularly good for bathrooms because it tolerates changes between very damp and very dry conditions without cracking.

To reduce dust accumulating on walls, vertical panelling should be preferred. Interior panelling can best be re-used if it can be removed without damage, and should be fixed so that it is easily removable.

Shakes and shingles can be mounted onto the exterior walls following the same method as for roofing. The problem of water gathering is much less, and the lifespan is



15.25
Modern version of rebated shiplap panelling.

therefore longer. The oldest known preserved shingles are to be found on the walls of Borgund Stave church in Norway. They have been regularly painted every fourth year with wood tar since the thirteenth century.

Wattle walling is a construction of woven branches that has been used since prehistoric times. The dimensions of the plant material used can vary a great deal. The key to working it is elasticity. If the branches are flexible enough, they can be plaited on poles for several metres. There are two types of wattling: rough and light wattlework.

Rough wattlework has been done in birch, ash, pussy willow and rowan. The bark is removed and the ends burned until they are black, achieving a sort of impregnation. The usual length of branches to be plaited is about 3–4 m. Poles are fixed between the top and bottom plates of a wall at a distance of about 50 to 60 cm, then the branches are woven in between so that the top ends and root ends alternate. The layers are regularly pushed down to make them compact. Weaving can also be vertical, on battens fixed between vertical studwork.

In Denmark and further south in Europe, this wattlework is used as an underlay for a clay finish between the posts in timber framed buildings. In its purest form, this

15.26

Cladding with juniper exterior. Architect: Inga Lindstrøm.

technique can be used for visual barriers or windbreaks on terraces and balconies, or for walling in sheds, etc.

Lighter wattlework consists of twigs, often juniper with its needles intact, but birch and heather can also be used. The juniper is cut around midsummer, since that is when the twigs are toughest and the needles most firmly attached to the bush. The same can be said for birch, which can also be used with the leaves attached.

Branches of about 50 cm in length and 1–1.5 cm thickness are cut and woven between horizontal battens at 20 cm intervals so that each branch lies inside one batten and outside two, forming two layers outside and one layer inside each batten (Figures 15.26 and 15.27). The wattlework is pushed together with a hammer to make it tight. Finally the wall is trimmed. At first the cladding is green; in time it becomes brown and dark grey, and after 30 years so much moss may grow that it becomes green again.

Wattle cladding is as durable as timber cladding. Juniper cladding is particularly good, and has had a functional lifespan of between 50 and 60 years; and even up to 100 years in the western fjord landscape of Norway. During a period of this length in this particular area, it is usual to change timber panelling at least twice. A juniper wall also has the advantage of being maintenance-free, but the wall is relatively flammable and sparks from a bonfire or chimney can ignite it.

15.9.3 Wooden floors

Wooden floors give warmth and sound insulation. They are relatively soft, warm, physically comfortable and do not become electrostatically charged (unless treated with varnish). In addition, they can be hard-wearing and relatively resistant to chemicals. They need to be kept dry but maintenance requirements are moderate.

It is difficult to know when wooden flooring first appeared. In the countryside, rammed earth floors were still common as late as the Middle Ages, but in the towns, stronger, drier floors were needed. As well as stone and brick floors, wooden floors were quick to spread during this period. In buildings of several storeys there was no

15.27

Cladding with juniper interior. Architect: Inga Lindstrøm.

alternative. Planks and cleft tree trunks were used, usually on a system of joists or at ground level directly onto the earth.

Wooden floors are generally made of high quality spruce, pine, oak, beech, ash, elm, maple or birch. Aspen is less hard wearing, but is well-suited for bedrooms, for example. Aspen floors are soft and warm and have also been used in cowsheds and stables where they tolerate damp better than spruce and pine and do not splinter.

Wooden floors are durable, but should be thick enough to allow for sanding several times during their lifetime. Periodic sanding removes the worn or stained upper layer and can provide a floor as good as new,

15.28

on condition that the floor planks are thick enough to lose a few millimetres in this way over their lifetime. With underfloor heating, timber floors should be used with care due to possible cracking. The timber to be used for flooring is most often artificially dried, unlike other solid timber products, involving an increased use of energy in the production process. With the use of special construction methods (see Figure 15.28), the timber can be laid after being naturally dried to about 16–17% moisture. This can also be done for ordinary floor boarding by letting the boards lie together unfixed for half a year, after which they are fixed permanently.

A floor has to be treated after laying. This can be done with green soap, varnish, lye or different oils (see Chapter 18). Floors that are treated with lye, soap or linseed oil are warm and anti-static and good moisture regulators. Varnished floors are cold and vapour proof, but their shiny surfaces makes them easier to maintain. This is, however, only a short-term solution as the layer of varnish will slowly but surely split, especially where there is heavy traffic; then the floor needs sanding and re-varnishing. Oiled floors are renewed by just repeating the treatment on the worn parts of the floor.

Solid wood is also often used in subfloors. Low quality spruce is adequate. This type of floor should ideally be allowed to settle for a year before laying the final floor covering.

TYPES OF WOODEN FLOORS

Solid timber floors are usually tongued and grooved, and used in thicknesses of 15–28 mm. They are preferably laid with the hardest wearing pith side upwards. There are two main principles for laying floors: the floating and the nailed floor.

In a floating floor the floorboards are glued together along the tongues and grooves. The floor lies free from the walls, and is held down by strong skirting boards. This method reduces the chance of recycling as it is difficult to remove the floor without damaging or breaking it.

In the nailed floor the floorboards are fixed to the joists with nails and no glue. To make re-use easier, the nails should be nailed through the boards from the top and straight down. This is, however, seldom done.

Batten flooring is a mixture of the first two methods (see Figure 15.28). Here, the floorboards are locked into position by battens of hardwood. Re-use possibilities are very high. This floor can be laid without being dried in a chamber drier, because it is easy to move the boards closer together later on by loosening the battens. Unlike other timber floors, in batten flooring individual floorboards can easily be changed.

Parquet. The material normally used for parquet flooring is hardwood such as oak and beech. Birch and ash can also be used. These are sawn into long boards of 50 to 130 cm or short boards of 15 to 50 cm, and are tongued and grooved. The short board is normally 14 to 16 mm thick; the long board is 20 mm thick. The breadth varies from 4 to 8 cm. A number of laminated parquet floors have a top layer of hardwood 4 to 6 mm thick glued onto a softwood base of chipboard. Urea-formaldehyde glue is usually used for this. Parquet flooring is nailed or glued directly to the floor structure or onto a floor base. It can also be laid with bitumen-based glue onto a concrete floor or onto battens in a sand base.

Timber cubes are usually rectangular and placed on an underlay with the grain facing upwards. Spruce, pine or oak can be used. This type of floor is comfortable to walk on and it effectively suppresses the sound of steps. It is hard-wearing, and very suitable for workshops. It is easy to repair and tolerates alkalis and oils, but expands in response to damp and water and should not be washed heavily. The cubes are usually 4 to 10 cm high. The proportion of length to breadth should not exceed 3:1. Off-cuts from a building site can be used. The cubes are laid in sand, and the joints are filled with cork or sand and then saturated in linseed oil. On industrial premises it is usual to dip them in warm asphalt before setting them.

15.9.4 Natural rubber (latex)

Natural rubber is used as a flooring material. Rubber coverings contain 2% sulphur powder by weight, 50–60% fillers of kaolin and chalk and about 5% of pigments. Vulcanizing agents and often ultraviolet stabilizers, fire retardants and lubricants are also added in proportions of 2–3%. Zinc oxide is much used as a fire retardant, and the lubricant is most often stearine, an ester from stearic acid derived from animal fat.

15.9.5 Wood-based boards

There are, in principle, three types of boarding made from ground timber: fibreboard, chipboard and cork sheeting. Plywood boards on the other hand are usually made of larger, very thin wood sheets laminated together.

Wood-based boards are mainly used for interior purposes, but can, with the use of waterproof glueing and appropriate surface treatment, also be used as external cladding. However, experience so far has shown exterior solutions to be vulnerable in harsh climate conditions (Bøhlerengen, 2001). Plywood is most often exposed as internal cladding. Fibreboard and chipboard are almost exclusively used as an underlay on either floors or walls. On floors, they can provide the base for a 'floating' wooden floor or soft floor coverings; on walls and ceilings they can provide a base for wallpapering, hessian or paint. Some products are delivered from factories with these finishes already mounted. Laminate flooring is often made up of chipboard covered with a plastic laminate. Cork flooring is a soft floor covering, 3–5 mm thick and therefore dependent on a firm subfloor. The cork is often coated with a protective layer of polyvinyl chloride or polyurethane. Natural waxes can also be used.

Fibreboards are produced in porous, semi-hard and hard variations from defibrated wood fibres. The products are often glued by their own glue which forms through heating in a wet process (see page 280). But for semi-hard and hard products, small portions of additional glue are often added anyway. In the alternative dry process, the portion of glue is increased (see Table 15.9). Fibreboards produced in the dry process are widely known as *medium-density fibreboard* (MDF) and *high-density fibreboard* (HDF). MDF boards are regularly used in the production of furniture. Cork sheeting made from broken bark from the cork oak could also utilize its own glue, although additional glues are most often mixed in as well (see Table 15.9). As a non-synthetic alternative, a resin based on cashew nut oil can be used. In the laminating of plywood, additional glue is a necessity and is used to fix from 3 to 6 and more layers of wood sheeting laid across each other. Traditional chipboard is produced from ground timber waste. *Oriented strand board* (OSB) is a

Table 15.9 *Adhesives in wood-based boards, see details on adhesives in Chapter 17*

Material	*Types of adhesive*	*Amounts of adhesive (%)*
Wood fibre boards, wet process	None or Phenol-formaldehyde PF	1
Wood fibre boards, dry process	Polyurethane PU, Phenol-formaldehyde PF or Urea-formaldehyde UF	4–10
Chip board	Urea-formaldehyde UF or Phenol-formaldehyde PF	10
Oriented strand board	Methylene-diphenyl-isocyanate MDI, Phenol-formaldehyde PF, Melamin-urea-phenol-formaldehyde MUPF or Polyurethane PU	3–6
Plywood	Urea-formaldehyde UF or Phenol-formaldehyde PF	2
Cork sheeting	None, Phenol-formaldehyde PF, Polyurethane PU or Urea-formaldehyde UF	2

Note: Some products will contain several types of adhesive.

fairly recent version of chipboard based on wood strands. A wide range of glues are used in chipboard (see Table 15.9).

Several wood-based boards may have fire retardants, waterproofing agents and other additives; although not so much in products for indoor use. For the plastic coating of particle boards and fibreboards, melamine formaldehyde (MF) is usually used.

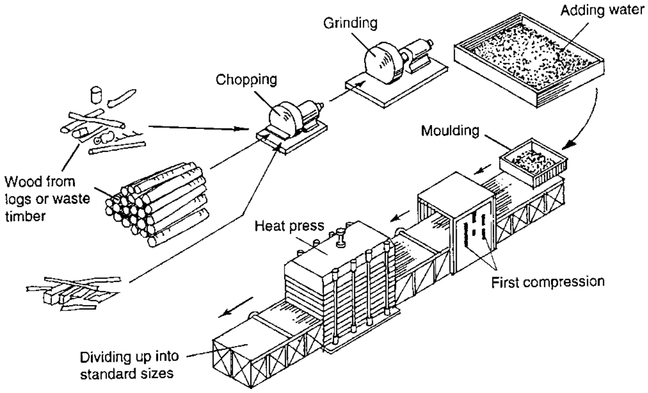
The quality of timber for veneers has to be good. Low quality raw material is used for traditional chipboard in particular. Here the use of poplar and willow is an interesting option as such species absorb more carbon dioxide per hectare and year than most other tree species (see Table 10.6). It is possible to recycle demolished chipboard into new chipboard by hydrolysis of UF adhesives with steam at 110 °C. In oriented strand boards, fresh wood is normally used. Production of fibreboard through the wet process needs mostly fresh wood where the natural glues are still available. In the production of fibreboard by the dry process method, demolition waste can be used as a basis resource. Methods have been developed for recycling used fibreboards to make new boards (Athanassiadou *et al.*, 2005). Up to 15% of the recycled material can be mixed in with new material. To some extent, residues of the natural glues in the old material are reactivated in the process, reducing the amount of new glue required.

PRODUCTION OF WOOD-BASED BOARDS

Fibreboards. The production of porous wood fibreboards in both a wet and dry production process are described in Chapter 14 (page 280). The processes are similar for semi-hard and hard products (Figure 15.29).

Chipboard and ***Oriented strand board (OSB)*** can be made from many types of timber. There is no need for the timber to have its own active glue, as the process includes gluing. Urea-formaldehyde glue is used for both economical and technical reasons, but different melamine glues, phenol-formaldehyde-resorcinol glue and polyurethane glue may be used, and possibly also timber-based lignin glue and water-glass glue. The manufacturing process of chipboard is as follows:

1. The timber is shredded.
2. The shredded timber is ground to small particles or strands, the latter used in OSB boards.



15.29

Production of hard and semi-hard wood fibreboards.

3. The shavings are dried to a moisture content of about 2%.
4. Glue is added. The amount of glue by weight is approximately 3–12% and is lowest in OSB boards due to the removal of fine particles.
5. The pulp is made into a sheet on a moving band. OSB boards are usually built up in three layers with different strand orientation.
6. The sheet is then pressed at 180–200 °C.
7. The boards are dried and conditioned to the desired moisture content.

Plywood is produced in different forms and from many different types of timber, including tropical species, by sawing, cutting by knife or peeling. Sawn plywood is mainly used in the production of furniture and is produced by sawing the log along its length in thicknesses of 1.5 mm or more. The other two types of cutting are used on logs that have been boiled or steamed until they are soft and pliable. Cutting by knife is done along the length of the log as with sawing. By peeling, the veneer is peeled off the rotating log like paper pulled from a kitchen roll. A plywood board is made by gluing several layers of the veneers together. This can be done in two ways, to make blockboard sheeting or plywood sheeting. Blockboard consists of wooden core strips glued together, usually of pine, which are covered on both sides with one or two veneers. Plywood consists purely of different veneer layers glued together. The adhesive used nowadays is usually urea or phenol glue in a proportion of about 2% by weight. Animal, casein and soya glue give good results as well.

15.10 GRASS MATERIALS

Basic info is found in Chapter 10.

Throughout European history plants have been used as roof and wall-cladding; in general, the different types of grasses such as wheat, rye, flax, oats, barley, marram grass, reeds, ribbon grass, greater pond sedge, fern and eelgrass. Plants can be used for thatching as they are, possibly cleaned of seeds and leaves. Several species can also be used to make boards, and oil from the flax plant is the basic raw material for making soft floor coverings of linoleum. In addition to the ordinary conditions a surface material has to fulfil, plant materials often give a high level of thermal insulation and good moisture buffering properties. Many of these materials are flammable and susceptible to rot. However, eelgrass contains salt, lime and silica and is relatively hard to ignite as well as quite resistant to mould.

In excavations made in Lauenburg, Germany, there are indications that buildings were thatched with straw as long ago as 750–400 BC. In Denmark, this type of roof is believed to have been in use for at least 2000 years. The use of thatched roofs has decreased considerably; this is partially due to insurance companies demanding higher premiums for what is perceived as a high fire risk, and partially because of the mechanization of agriculture (straw that has gone through a combine harvester is unusable). In Germany and the Netherlands, reeds have almost become non-existent due to land drainage. In Western Europe today the raw material is imported from Poland, Bulgaria and Romania. Even Denmark has difficulty supplying its local needs. Conversely, in Africa and Asia, roofs built from local plants still dominate many cultures. In India, for example, 40 million houses are covered with palm leaves, reeds and straw.

Ecologically speaking, grass materials for surface applications are very attractive. They are renewable resources taken from uncultivated areas, or else by-products of agriculture and food production. The production processes do not require much energy or generate pollution.

In buildings, grass materials don't usually have problems. Building boards, however, often have adhesives added, such as polyurethane glue which can emit small amounts of unreacted isocyanates. Fresh linoleum can emit aldehydes. There has also been evidence of emissions from added solvents, glues and plastic-based surface coatings if these have been used. The differences in these emissions can be large, depending on the manufacturer.

As waste, the pure products can be composted or burned for energy recovery. When composted, special care should be taken to avoid eutrophication of ground water. For products containing adhesives, special waste treatment and incineration is required.

15.10.1 Roofing and wall cladding with grasses

Grass claddings have good insulation properties both with respect to heat and sound, and many different plant species can be used (see Table 10.8). Harvesting and laying methods for all coverings are labour-intensive, although parts of the harvesting process for reeds could be mechanized relatively easily. In Denmark, a mobile harvesting machine for straw roof coverings is in use. Here, the grain is removed without destroying the straw. During the three month long summer season this harvesting machine can produce straw for 200 roofs covering 180 m^2 each.

The durability of thatch depends upon the growing conditions and how the plant was cultivated. A sunny climate without nightly frost is best. Straw and reeds which are used on the continent today are nearly all artificially fertilized, which produces enlarged and spongy cell growth resulting in a far shorter lifespan than necessary (Table 15.10).

Strong sun generally causes splits and breaks down thatched roofs – they survive longer in Northern Europe than further south, for instance. At the same time, there can also be a different lifespan on the north and south-facing parts of a roof. Eelgrass probably has the longest lifespan of all thatching materials. The most stable of the cultivated grain straws is generally said to be rye.

Table 15.10 *Longevity of roof coverings and exterior cladding based on grasses, experiences of Northern Europe*

Species	*Unfertilized/fertilized naturally (years)*	*Artificially fertilized (years)*
Bracken	8–10	
Eelgrass	200–300	
Heather	More than 25	
Reed	50–100	30
Straw from rye/wheat	20–35	10–12

(Source: Hall, 1981; Stanek, 1980)

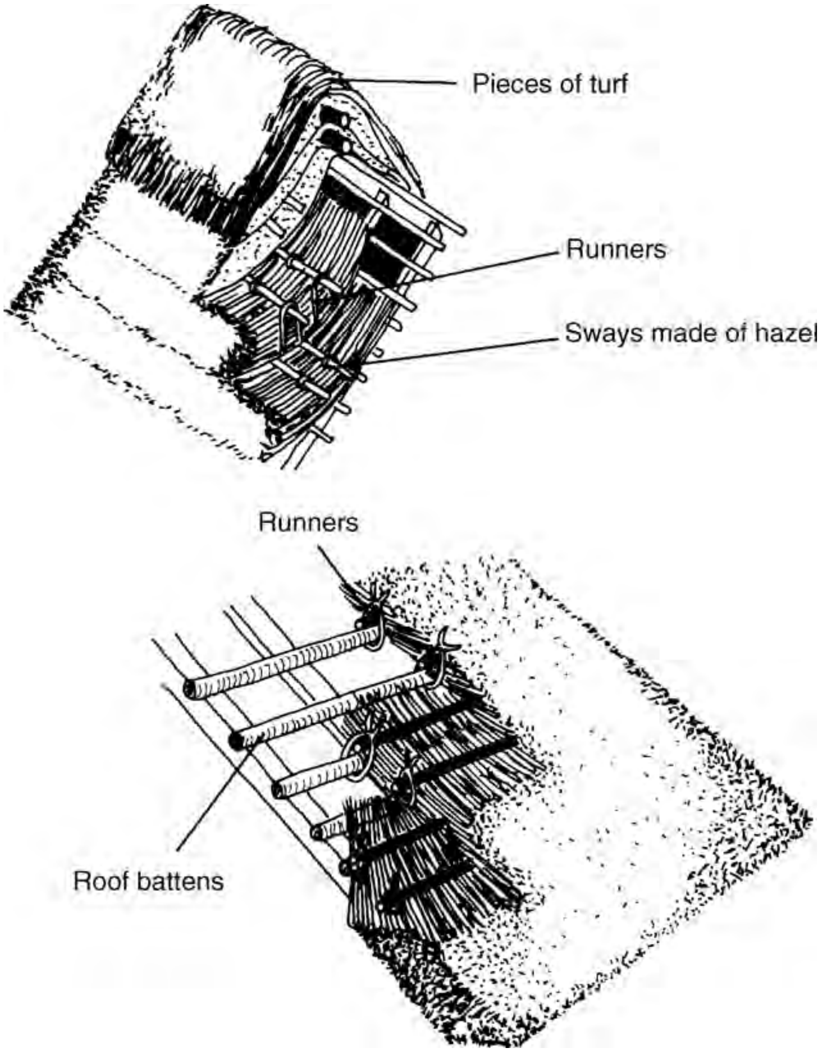
METHODS FOR THATCHING WITH STRAW

Roofing. When thatching a roof with straw a series of battens (sways) are erected on the rafters at 30 cm intervals. The straw is bundled together and carefully threshed without destroying the stalks. Weeds and loose straws are combed out with a special comb. The bundles are laid edge-to-edge on these battens, one layer on each sway. Every layer is bound down by runners that are fastened to the sways, preferably with coconut twine. The completed roof is trimmed, using special knives, to a thickness of approximately 35 cm. The ridge is usually made with turf cut into 1 to 2 metre long pieces. On the inside of the rafters it has been the custom more recently to place fire-resistant insulation boards of woodwool cement. Good ventilation from the underside of the roof is important. As with timber roofs, the rule of the steeper the roof, the longer it lasts, applies. The usual slope in normal climatic conditions is 45°, whilst along the coast it should be up to 50° (Figure 15.30).

METHODS FOR THATCHING WITH EELGRASS

Roofing. (Figure 15.31) A layer of twigs (preferably pine or juniper) is placed on battens at 30 cm intervals. The eelgrass is worked and shaken to get rid of lumps and to make the straws lie in the same direction. Sections of eelgrass are then wrung hard to form 3 metre long scallops, in the same way one wrings water out of a floor cloth. The scallops continue out into a long, thin neck that acts as a fastening loop to the battens. The scallops are fastened tightly together on the four to five lower battens, and the rest of the roof is built up with loose eelgrass laid in layers and pulled well together. By mounting a buffer along the roof's edge similar to the turf mound on a turf roof, it is possible to manage without scallops. The roof needs to settle for a few months before a second layer is added. The total thickness is usually 60–80 cm, but there are examples of 3 metre thick roofs – which must be one of history's warmest roofs ever. After the final layer, the thatching is cut level with a special knife. The ridge is often covered with a long strip of turf. This could be replaced with a layer of eelgrass kneaded in clay. After a few years the roof will settle down and become a solid mass with the consistency of flaked tobacco. The time is then ripe for a new layer. Rain only gets through the outside layer and then trickles slowly down to the edge of the roof. At the same time the roof is open to vapour coming from the inside of the house.

Wall cladding with eelgrass was traditionally most often used for gables, using 10 cm thick layers of combed seaweed of about 60–70 cm in length. These bundles were stuffed between vertical battens at 30 cm intervals. Every layer was fixed by a horizontal branch woven between the battens. Finally, the gable was cropped with a long knife



15.30

Details of roof thatching with straw.
Source: Grützmacher, 1981.

so that it had a smooth even surface. Like eelgrass roofing, the eelgrass gable has a very high durability, but with time will settle, and cracks must be refilled.

15.10.2 Grass boarding

The most common raw materials for the production of boards are wheat, hemp, rye, oats, barley, reeds, rape, flax and maize. It is generally straw produced from these plants that is used. Decomposed plant fibres in the form of peat can also be compressed into boards. The technical properties of hardboards are similar to those of conventional chipboard. However, they are mainly used internally as a base cladding, although in some cases they are used as external cladding.

Hardboards are produced in a range of thicknesses between 3 and 13 mm and can have tongue-and-groove or lap joint edges. Porous boards with good thermal and acoustic properties are also produced, in thicknesses up to 100 mm. The products are often used in demountable partition wall systems.

15.31

Thatching with eelgrass at Læsø (Denmark).

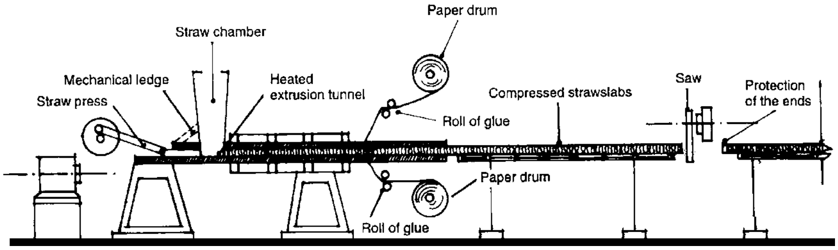
Many types of straw contain natural resins that can be used to glue the boards together. This includes wheat, hemp, flax and barley. The effect can be stimulated by treating the straw with laccase (see page 178). In most products, however, glue is added. Polyurethane adhesive (PUR) is often added in lighter products while methylene-diphenyl-isocyanate (MDI) is often used in high-density boards. High-density flax boards are usually produced without additional glue – instead the fibres are boiled for a few hours before the boards are processed.

Boards made of straw are not particularly resistant to vermin, and when used externally they often have to be impregnated with fungicides. If they are rendered, the problem is considerably reduced. The alkaline properties of the render prevent the growth of mould.

PRODUCTION OF LOW-DENSITY STRAWBOARDS

The manufacture of low-density strawboards follows a process developed in Sweden in 1935 and is suitable for local production in small industrial units (see Figure 15.32). The boards are usually produced in thicknesses of 50 to 100 mm. It does not matter what state the straw is in, as long as it is not beginning to rot. The moisture content before the process starts should be 6–10%. The procedure is as follows:

1. The straw is cleaned in a ventilation unit.



15.32
Production of strawboards.
Source: Stramit.

2. The fibres are straightened and laid in the same direction. If extra adhesive is required, it is added at this stage, usually in the form of a polyurethane glue in a proportion of about 3–6% by weight.
3. The boards are put under pressure in a closed chamber at a temperature of 200 °C.
4. The boards are cooled.
5. The boards are cut to size.
6. The boards are coated with an adhesive and covered with a stiff cellulose paper, preferably recycled, which gives them rigidity. The paper should also be treated with a water repellent, such as a latex solution.

15.10.3 Soft floor covering of linoleum

Linoleum was first produced in England in 1864 and is made in thicknesses of 1.6–7 mm. A normal manufacturing procedure is to first boil linseed oil (23% by weight) with a drying agent, usually zinc (about 1%), and let it oxidize. This is mixed with 8% softwood resin and 5% cork flour, 30% wood flour, 18% limestone powder and 4% colour pigments, primarily titanium oxide. The mixture is granulated and rolled while heated on a jute cloth (11%) that is hung to oxidize at 50–80 °C.

Most manufacturers cover the linoleum with a layer of acrylate to make it easier to roll and stay clean. In certain cases polyvinyl chloride is used. Linoleum with no surface coating should be waxed before use. Several linoleum products are also provided with an elastic underlayer to make it soft enough to walk on and to reduce impact noise. This is usually based on foamed polyethylene or cork.

In smaller rooms, linoleum can be laid loose and held in position by the skirting. This will make it easier to renew worn out coverings. It is, however, normal to glue linoleum to the floor, but this should not be done before the base onto which it is glued is fully dry. Ideally, a concrete floor needs more than a year to dry out. If a floor finish is glued too early, fungus can form in the glue, spread to the floor construction and walls and even eat the linoleum. The adhesives usually used are acrylate glues, ethylene-vinyl-acetate (EVA) and polyvinyl-acetate (PVAC). Glue based on natural latex in a solution of alcohol can also be used.

Linoleum does not tolerate continuous heavy exposure to water and is therefore not suitable for bathrooms.

15.11 BOARDING FROM DOMESTIC WASTE

Boards can be made of domestic waste for use as chipboard-like underlayers for different finishes on walls and floors. Several products have been developed, all primarily using the fibre fractions of the waste materials.

One alternative is produced from used beverage cartons containing polyethylene. The cartons are sorted, shredded, heated and cut into 5 mm particles. The material is then spread into sheets, compressed, heated again and pressed between two plates. The polyethylene content in the material melts, acting as a glue to bond the board, thus making it durable. The board is then cooled in a cooling press and pressed once again to strengthen it.

Another alternative is produced mainly from worn corrugated paper containers that are mixed with water and ground up in a hydrapulper. The slurry is poured into moulds. Any remaining water is removed under heat and pressure, creating sheets without the need of any additional adhesives. One face is strengthened with 'honeycomb' patterned ribs. Two sheets are then laminated together to form boards approximately 19 mm thick using polyvinyl-acetate glue (PVAC).

Different textile fibres with mixed composition can be used for producing composite panels in the same way as with chipboard, where the dry mass is mixed with glue in portions of 10–15% and exposed to heat and pressure (Gomes *et al.*, 2007). Smaller amounts of stronger fibres, such as sisal, are added to provide extra strength.

Tests are also being conducted to produce boards from unsorted mixed rubbish. The rubbish is crushed and ground. Metals are separated out by electromagnets and the rest is dried at 140 °C to a moisture content of 3–5%. Centrifuging removes the heavier fractions in the rubbish. The heavy part is returned to waste and the light rubbish, being mainly paper, plastic and food leftovers, is mixed with about 50% wood pulp. The mixture is then glued under pressure.

The use of waste as a raw material is optimal, environmentally speaking. However, some of the products may contain contaminants from plastics and other materials, which can affect the indoor climate. There is also a risk of emissions from binding agents and fungicides that may have been used. Most waste products can be used as raw materials for the production of building boards, although usually at a slightly lower level of quality. Useless waste must be deposited at controlled tips or energy-recycled.

15.12 CARPETS AND TEXTILES

Basic info is found in Chapters 9, 10 and 11.

Carpet as a floor covering has the primary function of providing a more comfortable surface to walk on. It is soft, has little thermal conductivity, and a good noise absorption capacity. Carpeting can be woven, knitted, tufted or needle-punched in many different natural fibres: cotton, wool, bristles, sisal, coconut fibres (coir), jute (hessian) and hemp, as well as in synthetic fibres such as nylon, acryl, polypropylene, polyacrylnitrile, polyester and rayon.

In the East, carpeting has been used for centuries. In Europe, hides have traditionally been used as carpets. Here the first true carpets originated about 200 years ago. Until then, people managed with natural materials strewn on the floor: juniper or bracken, sawdust or sand, which absorbed dust and damp. This kept the floor clean, as it was regularly changed. In the 1960s, wall-to-wall carpeting was introduced, transforming the carpet from a loose floor covering to an independent floor covering, often laid directly onto a base of concrete. The spread of this type of covering was very rapid, in housing and in buildings such as schools, offices, public buildings, etc. In the beginning, natural fibres were used, but synthetic fibres soon took over, making up half of the market by 1967 and the majority of the market today.

The procedure used for the production of carpets varies according to the technique and material used. Weaving and knitting requires spun thread. Needle-punched carpets are made of unspun wool. For needle-punched and tufted carpets, a carpet backing in one or two layers is used to keep the fibres in place and add strength, stability and elasticity. The backing usually consists of a woven underlay of fibreglass, jute or propylene coated with styrene-butadiene rubber (SBR), foamed polyurethane, polyvinyl chloride or natural latex, and is most often glued to the textile layer with polyvinyl-acetate (PVAC), ethylene-vinyl-acetate (EVA), acrylate adhesives or bitumen. Products with polyvinyl chloride usually have phthalates added as softeners. A modified backing can also be used for some woven and knitted products.

All carpets, both natural and synthetic, can contain flame retardants including chlorinated and brominated hydrocarbons, anti-static agents, and substances to protect them against moths and fungus, often ammonium compounds. Woollen products are often impregnated with pyrethrin. Jute may have been sprayed with chemicals during its cultivation or at the time of transport, in some cases with DDT.

Loose carpets are laid directly onto an existing floor. Fitted carpets are usually laid on an underlay of polyvinyl chloride, polyurethane or foamed synthetic rubber; latex, cork, woollen felt and hessian are alternatives. The carpets are fixed to the floor with skirting boards or glue. Different sorts of glues, such as PVAC and acrylate adhesives, can be used. Joints are sewn or glued.

European renewable raw materials for the production of carpeting are wool, flax, eelgrass, hemp and nettles. Timber is the raw material for rayon. Sisal comes from Mexico, whilst coconut is found in the tropics, where it is often a major resource. Synthetic fibres such as polyamide, polypropylene and polyacryl are all based on fossil oils. These days, some products can contain a certain proportion of recycled plastics. The energy needed for the production of plastic-based products is high, and a wide range of pollutants can be emitted, including large amounts of carbon dioxide.

All carpets contribute to the gathering and distribution of dust into the indoor air. Alarming emissions from glues, plastic components, fungicides, etc. have also been recorded (Ehmsperger *et al.*, 2006). Synthetic carpets can lead to electrostatic charging of the inhabitants, which in turn can lead to irritation of the mucous membranes.

The durability of carpets is relatively low. If they are glued, removing them can be difficult. However, the market now includes leasing systems whereby the carpeting is delivered in fairly small tiles that can easily be replaced as needed.

Wall-to-wall carpeting has little chance of being re-used, and probably hardly any chance of being recycled because of the many different materials it contains. Most carpets can be burned for energy recovery in incinerators with special filters. The emission of carbon dioxide when burning plastic materials is similar to the burning of oil. Ash and waste from plastic products and natural products with plastic-based glues, toxins against mould, etc. have to be deposited at special tips. Carpets of pure natural fibres can be composted.

15.13 WALLPAPERS

Basic info is found in Chapters 9, 10 and 11.

Wallpapers have a primarily decorative purpose within a building (in the same way as painting does) but can also have a role (intended or not) as a moisture regulator or vapour membrane. This depends upon the type of material used. Wallpapering a room with a heavy pattern or an illustrated theme will make its mark. Most of us can remember the rabbit wallpaper in our childhood bedroom. Oscar Wilde declared on his death bed: ‘The wallpaper or me. One of us has to go!’

William Morris, the great wallpaper designer of the Arts and Crafts movement, stated: ‘No matter what you are going to use the room for, think about the walls, it is these that make a house into a home’ (Greysmith, 1976). There are four main types of wallpaper:

- Wallpapers based on natural textiles.
- Synthetic textile wallpapers.
- Paper wallpapers.
- Plastic wallpapers.

Paper and textile wallpapers are best suited for dry rooms, whilst plastic wallpapers can also be used in bathrooms, washrooms, etc.

Wallpaper can be tacked or pasted onto different surfaces such as oriented strand boards, plasterboards or smooth rendered concrete. It is important that the concrete has dried out properly so as to not cause damp patches or mould.

HISTORY

Textiles inside buildings have a long history. They were initially used for dividing rooms as, for instance, in Japanese architecture. The Assyrians and Babylonians were probably the first to paste them onto existing walls. In England, textile wallpapers were produced during the fourteenth century. In the beginning they were woven and embroidered like a tapestry, which meant that they were in a price class that only kings could afford. During the fifteenth century, the Dutch began painting

15.33

Grafton Wallpaper designed by William Morris, 1883.

simple figures and ornamentation onto untreated linen. The price of wallpaper dropped a bit, and rich merchants, statesmen and higher church officials could afford it.

About 100 years later waxcloth wallpaper arrived, which consisted of a simple sacking of hemp, jute or flax covered with a mixture of beeswax and turpentine. A pattern could be printed on the surface. Waxed wallpaper was much cheaper than the earlier types of wallpaper, but it was only when it was being made from paper that prices fell and everyone had a chance of buying it. It was first available in 1510, initially as small square pieces of paper in different colours, pasted up as a chequered pattern. During the eighteenth century, the first rolls of wallpaper came on the market with hand printed patterns, and around 1850 the first machine printed wallpapers arrived.

An analysis of the many wallpaper patterns throughout history gives a good indication of cultural trends. William Morris's organic, flowery wallpapers tell of the great need to keep in touch with nature during industrialization's first epoch (Figure 15.33). Something of the same longing can be seen today on the panoramic photographic views of South Sea Islands, sunsets, etc.

Wallpapers of natural textiles are most often produced with fibres of jute or cellulose. Other fibres like wool, flax, sugar cane, silk, hemp and cotton can also be used. The textile fibres are woven together and glued to an underlay of cellulose, viscose or plastic. One particular wallpaper is made with rye straw woven together with cotton threads. Some products will have water repellents, flame retardants and fungicides added. They can also be dyed, and dye fixers can contain heavy metals. Wallpapers of natural textiles can offer a substantial contribution to the buffering of moisture in the indoor climate.

Wallpapers from synthetic textiles are mainly woven with fibreglass. The fibreglass is often used in combination with polyester thread. This is usually given a coating of paint based on polyvinylacetate (PVAC) or acrylates to prevent it from losing fibres. It is also common to add fibreglass to an otherwise pure natural textile in order to strengthen it.

Paper wallpaper is made from cellulose, often in the form of recycled paper. Some products are bleached with chlorine. Amounts of small wood shavings can be added to form a structure. In certain products a thin plastic coating is used to increase resistance to water and improve wash-ability. Printed patterns are often based on animal glue paint, emulsion, oil or alkyd paint to a total share of 15–20% of the total weight of the wallpaper.

Plastic wallpaper is produced from polyvinyl chloride (PVC) fixed in a structure of paper or natural textile, and can be smooth or textured. The PVC has phthalates added as softeners. The products can also contain flame retardants and fungicides.

All wallpapers are glued to the underlayer. For paper products, starch glues and glues based on methyl cellulose are mostly used. Heavier products are usually glued with PVAC. The glues can have biocides added.

Fibreglass fabric is made from quartz sand, which can be found in abundance. Plastic products are based on fossil oils. Wallpapers of natural textiles are based mainly on renewable raw materials. When recycled cellulose is used, the consumption of energy and water in production is substantially reduced.

Most plastic wallpapers and other products with a plastic coating have low vapour permeability, which means that moisture buffering properties in the underlayer will be less accessible. Considerable emissions of styrene have been measured from fibreglass reinforced polyester wallpaper, increasing in damp environments (Gustafsson, 1990). Products of PVC emit phthalates and several other compounds that may irritate the mucous membranes. In some of the used glues, mould can arise when exposed to continuous damp. Large amounts of dust can also gather on rough textile coverings, creating a basis for growth of mould and dust mites. Dust can collect on plastic wallpapers due to electrostatic charging with the same effect. Wallpapers of PVC also become sticky if they are heated (for example, when situated close to heating systems) and emit more gases.When renovating or demolishing, it is usual to remove old wallpaper from walls. This is quite easy with paper wallpapers. Steam or hot water can be used on the soluble pastes. It is more difficult with plastic wallpapers. Products in bathrooms with a foamed underlay of PVC are almost impossible to remove, and will often take a piece of the wall or plaster with them.

Wallpapers have no recycling value. Paper and natural textiles can be composted providing they have no polluting or potentially dangerous additives or adhesives. Fibreglass wallpapers containing polyester, and PVC wallpapers, have to be deposited on special tips. They can be burned for energy recovery if the incinerator is provided with special smoke filters and the ash is taken care of.

ENVIRONMENTAL PROFILES OF SURFACE MATERIALS (TABLE 15.11)

RULES OF READING

The estimates and evaluations are made per m^2 layer and a house lifespan of 50 years.

The volumes of materials and the loss factors are estimated on the basis of conventional practice.

The effects of additional material properties, such as thermal storage capacity and structural properties, are not included.

Calculation of global warming potential GWP include carbonatation (50 years), storing of carbon (50 years) and emissions from final incineration of products based on fossil fuels. The storing of carbon is calculated from net weight of material (exclusive loss and renewal).

The environmental evaluations are rated best = 1, average = 2 and worst alternative = 3. The *Environmental potential* columns indicate potentials for recycling and local production. The final environmental profile is suggested on the basis of subjective judgement from the author and are open to debate. On the basis of information in Table 1.4 and Table 2.8 alternative evaluations can be made. Also note the results in the GWP column, since global warming potential is often considered as a relevant overall indicator for environmental impact.

Table 15.11a *Roofing*

Material	*Durability (years)*	*Loss factor (%)*	*Quantity of material needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO_2-equ./m^2 50 years)*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Corrugated galvanized steel sheeting from ore, 6.8 kg/m^2	30	15	13	29	3	3	3	3	√		**3**
Corrugated aluminium sheeting from ore, 2.4 kg/m^2	50	15	2.8	42	3	2	3	2	√		**3**
Copper sheeting from ore, 5.4 kg/m^2	50	12	6.0	36	3	3	3	3	√		**3**
Concrete tiles, 50 kg/m^2	50	3	52	7.3	2	2	2	2		√	**2**
Corrugated fibre reinforced cement slabs, 13 kg/m^2	35	10	20	6.5	2	2	2	2		√	**2**
Slate, 85 kg/m^2	50	5	90	1.3	1	1	1	1	√	√	**1**
Fired clay tiles, 35 kg/m^2	50	3	36	6.8	2	2	2	1	√	√	**2**
Bitumen sheeting, 5.2 kg/m^2	25	10	12	14	3	3	3	3			**3**
Polyvinyl chloride sheeting, 2 kg/m^2	25	10	4.4	19	3	3	3	3			**3**
Timber, untreated, 18 kg/m^2	15	20	69	8.0	2	2	1	1		√	**2**

Table 15.11b *External cladding*

Material	*Durability (years)*	*Loss factor (%)*	*Quantity of material needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO$_2$-equ./ m^2 50 years)*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Galvanized steel sheeting from ore, 3.7 kg/m^2	35	15	6.1	13	3	2	3	3	√		**3**
Aluminium sheeting from ore, 1.6 kg/m^2	50	15	1.8	27	3	2	3	2	√		**3**
Fibre reinforced cement slabs, 20 kg/m^2	50	10	22	7.0	2	2	2	2		√	**2**
Portland cement plaster, 90 kg/m^2	40	10	124	20	2	2	2	2		√	**2**
Lime sandstone veneer, 96 kg/m^2	50	11	107	15	2	2	2	2			**2**
Lime plaster, 85 kg/m^2	40	10	117	8.2	2	2	1	2		√	**2**
Slate, 85 kg/m^2	50	5	90	1.3	1	1	1	1	√	√	**1**
Brick veneer, 108 kg/m^2	50	10	118	23	2	3	3	2	√	√	**3**
Timber, untreated, 14 kg/m^2	40	20	21	–8.6	1	1	1	1		√	**1**

Table 15.11c *Internal cladding*

Material	*Durability (years)*	*Loss factor (%)*	*Quantity of material needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO_2-equ./m^2 50 years)*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Stainless steel from ore, 3.8 kg/m^2	50	15	4.4	9.7	3	1	3	3	√		**3**
Fibre reinforced cement slabs, 20 kg/m^2	50	10	22	7.0	2	2	2	2		√	**2**
Portland cement plaster, 90 kg/m^2	50	10	99	16	2	2	3	2		√	**2**
Lime sandstone veneer, 96 kg/m^2	50	11	106	15	2	2	3	2			**2**
Lime plaster, 85 kg/m^2	50	10	93	6.5	2	2	2	2		√	**2**
Calcium silicate sheeting, 11 kg/m^2	30	15	21	2.8	2	1	2	2			**2**
Plasterboard, 12 kg/m^2	30	15	23	5.8	2	2	2	2			**2**
Loam plaster, 85 kg/m^2	30	5	141	2.8	1	2	1	1	√	√	**1**
Brick veneer, 108 kg/m^2	50	10	119	23	2	3	3	2	√	√	**3**
Ceramic tiles, 10 kg/m^2	50	10	11	6.3	1	2	2	2			**2**
Timber, untreated, 8.3 kg/m^2	50	20	10	−4	1	1	1	1	√	√	**1**
Wood fibre hardboards, 5.4 kg/m^2	50	10	5.9	4.4	1	2	2	1			**2**
Chipboard, 7.8 kg/m^2	50	10	8.6	1.3	2	2	2	3			**2**
Plywood, 4 kg/m^2	50	10	4.4	0.5	2	2	2	3			**2**

Table 15.11d *Flooring*

Material	*Durability (years)*	*Loss factor (%)*	*Quantity of material needed (kg/m^2 50 years)*	*Global warming potential GWP (kg CO$_2$-equ./m^2 50 years)*	*Environmental evaluations*						
					Effects on resources		*Effects of pollution*		*Env. potential*		*Env. profile*
					Materials	*Energy*	*Production and use*	*As waste*	*Recycling*	*Local production*	
Terrazzo tiles, 25 kg/m^2	50	10	28	2.2	2	1	1	2	√	√	**1**
Stone tiles, 30 kg/m^2	50	10	33	0.3	2	1	1	2	√	√	**1**
Brick tiles (30mm), 57 kg/m^2	50	10	63	12	2	2	2	2	√	√	**2**
Ceramic tiles, 14 kg/m^2	25	10	31	18	2	2	2	2			**2**
Polyvinyl chloride sheeting, 1.3 kg/m^2	15	10	4.8	21	3	3	3	3			**3**
Timber, untreated, kiln dried, 12 kg/m^2	50	20	14	1.0	1	1	1	1		√	**1**
Linoleum, 2.3 kg/m^2	20	10	6.3	5.5	2	2	1	2			**2**

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16 Windows, doors and stairs

16.1 WINDOWS AND DOORS

The word *window* originates from the Old Norse *vindauga*, a composition of *vindr* 'wind' and *auga* 'eye'. Windows bring in light, and views, and act as a protection from extremes of climate. A wide range of glass types has been used through history, from cut mica to float glass. A modern window is usually glazed with one large opening, perhaps in several layers, whilst windows in the past were glazed with multiple smaller panes separated by glazing bars due to the unavailability of large sheets of glass. Glazing bars were once made of lead, often strengthened by iron, within a main frame of timber. From the beginning of the eighteenth century, wooden glazing bars were used, and glass was kept in place with putty. Today there are four main types of window frame: timber, aluminium, steel and plastic. These are also used in different combinations.

The word *door* comes from Sanskrit and means 'the shutting of an opening'. The entrance door to a house was traditionally formed in a very special and careful way. The door was for receiving guests, as well as for greeting greater powers, both physical and supernatural, or for keeping them out. The material most often used is wood, but steel, aluminium and plastic doors are also made.

Both windows and doors can be seen as movable or fixed parts of the wall. They face the same demands as the external or internal wall: thermal insulation, sound insulation, resistance to the elements, security, etc. Not least, both windows and doors must be able to withstand mechanical wear and tear and keep their form and strength through varying moisture conditions. It has proved difficult to satisfy all these conditions. The thermal insulation of a modern outside door is three to five times less than the external wall, and a window's thermal insulation is four to ten times worse. Reducing the areas of glass will thus reduce energy demands more than using even the most effective energy windows and insulating frames. This is primarily an issue for the architect; how much glass does one really need? For example, if a classroom has a deep plan, it will need 20 to 25% glazing as opposed to a shallower plan classroom where 15% glass will suffice for daylighting (Traberg-Borup *et al.*, 2004). Windows placed high up in a wall also give more light than low windows.

16.1

A fortocha-window.
Source: Sergio Fox and Morten Kjærgaard.

THE FORTOCHA-WINDOW

The 'Fortocha'-window is a multifunctional window based on old Russian building traditions with two layers of glass in separate frames at some distance apart (Figure 16.1). The outer frame is equipped with a single glass to provide basic weather protection, and the inner frame with high performance double glazing to provide thermal comfort. There are openings at the bottom of the outer window and at the top of the inner window. Cold ventilation air is thus drawn in and preheated by the transmission heat being lost towards the outside. This provides draught free incoming air and minimal heat loss. The air space between the two frames at the same time effectively acts as a noise barrier as well as eliminating wind gusts, and limiting intake of particles of dust and pollen.

16.1.1 Glass and methods of installation

Float glass is normally used these days, though machine glass is still in production in some European factories (see page 99). Cast glass is used indoors, often as a decorative product that does not need to be fully transparent. There are various types of energy glass, security glass, sound insulating glass and fireproof glass. Energy glass is often slightly coloured or covered with a metallic oxide, such as tin, indium, antimony, silver or gold. Security glass is specially hardened or laminated with a foil of polyvinyl butyral between the sheets of glass. Sound insulating glass is also laminated in two or more layers. Fireproof glass usually consists of several layers laminated with sodium silicate. Glass that is self-cleaning by the addition of nanoparticles is now available.

Depending upon the level of insulation required there will be one, two or more layers of glass in windows (Table 16.1). There are several ways

Table 16.1 *Properties of window glass*

Types	*U–value (W/m^2 K)*	*Transmission of daylight (%)*
Single glazing	4.6–5.0	89–90
Double glazing	2.6–2.9	80–82
Double glazing with one low emissivity coating	1.4–1.8	74–78
Double sealed glazing with argon filling	2.5–2.6	80–82
Double sealed glazing with argon filling and one low emissivity coatings	1.2–1.4	74–78
Triple glazing	1.9–2.0	74–76
Triple glazing with two low emissivity coatings	1.0–1.1	62–67
Triple sealed glazing with argon filling	1.7–1.9	62–67
Triple sealed glazing with two low emissivity coatings and argon filling	0.8–0.9	62–67

Note: To maintain interior daylight quality, loss in transmission must be compensated by larger windows.

of achieving this. The easiest is to hinge two timber windows together, a traditional way of constructing windows in Scandinavia. A common way to fix the glass sheets in the frames is with putty based on acrylic polymers or linseed oil. Internal glazing can be mounted with special beading of wood or aluminium. Before using linseed oil putty on a window frame, the timber must be treated with oil or paint, otherwise the linseed oil will be absorbed by the window frame and the putty will crack.

Sealed units have become the most common type of glazing in the building industry. These consist of two or three sheets of glass with a layer of air sealed between them. The air can be replaced with an inert gas, such as argon, krypton and sulphur hexafluoride, which improves the thermal and/or sound insulation of the window because it is heavier or circulates slower than air. The sheets of glass are connected by plastic or metal spacers and sealed with elastic, plastic-based mastic. Until the late 1980s, polychlorinated biphenyls (PCBs) were widely used, but are now prohibited in most places because of their high toxicity. Most common today are products of silicone rubber, polysulphide rubber or polyurethane. Sheets of glass can also be welded together. The sealed units are usually fixed into a window frame with beads of wood or aluminium, together with rubber packing. It should be noted that the requirements for thermal insulation and noise insulation are completely different. For sound insulation, the glass layer should be as far apart as possible; for thermal insulation they should be a centimetre or less apart. This is because if the air gap is wider, the air between the panes will circulate, and the heat transfer from one side to the other will be significantly greater.

More recently, alternatives to glass have appeared on the market. These are mainly polymethyl metacrylate (plexiglass) and polycarbonate, which are often used in roof lighting, greenhouses and conservatories. The sheeting products are mounted in a similar way to the sealed units. These products are lightweight, easy to cut and mount, but are not always fully transparent. Some may discolour fairly rapidly in zones with high ultraviolet radiation, such as at high altitudes.

Glass for windows can be produced partly from recycled glass (about 20%). The rest is based on raw materials that have rich reserves, whilst production consumes large amounts of energy and generates pollution. Ingredients of plastic and metal oxides used also cause a high environmental impact both with respect to pollution and the use of resources. The same is true of most transparent plastic products that are based on fossil oils. The production of polycarbonate has bisphenol A as an important ingredient. In sealed windows, the use of krypton gas will reduce heat loss considerably compared to argon. However, the production of krypton is so energy intensive that this is more than outweighed over a building's lifetime (Krogh *et al.*, 2003). Sulphur hexafluoride SF_6 often used for sound proofing is a very potent greenhouse gas.

Glass coatings can reduce the transparency of the glass to such an extent that larger windows become necessary (see Table 16.1). Plastic and glass present no specific problems for the indoor climate, even though there may be small emissions from plastic-based putty, mastics and sealants, depending upon the type of plastic and the mounting technique.

Little is known about the durability of plastic rooflights. Normal glass has almost unlimited durability, but can be chemically broken down if exposed to lime, cement or calcium silicate paint. Coloured heat-absorbing glass can break if part of it is permanently in the shade and the rest is exposed to the sun.

Under special circumstances sealed units can have problems: at low temperatures, the pressure inside them drops, which bends the panes of glass inwards in the middle, giving a lower insulation value. If the building is not heated during the winter, the tension within the glass can be so great that it can break, especially if there is a wide enough space between the panes of glass. Otherwise, the weak link in these units is the seal or sealants. If they are not durable, moisture leaks in and condenses. If there is a vacuum or gas filling, this effect will be lost. In a penetrating durability test carried out by a Norwegian building research group in 1986, one third of metal-sealed windows were defunct after 20 to 32 years. For some of the plastic sealed types, nearly all were failing after four to five years (Gjelsvik *et al.*, 1986).

Another important aspect of sealed units is that if just one of the panes of glass splits, usually the whole window must be changed, whether it is double or triple glazing.

Sealed windows with a gas filling and special coating achieve the highest insulation values. In terms of use of material resources, there is little doubt that coupled timber windows give the best results; especially with a window divided into smaller panes on the outside, where the chance of breakage is highest. However, when one considers the lifecycle of a building, the energy balance will probably be best for one with sealed energy windows. But this is a complex calculation, which will also depend on local climatic conditions. The demolition phase should also be accounted for. Pure glass can be recycled for the production of new windows, while glass with metal coatings can only be recycled as bottle glass. Glass containing laminations of plastic foils, reinforcements, etc. will most often have to be dumped at controlled tips. The possible environmental effects of waste glass material containing nanoparticles is shrouded in some uncertainty (Meili, 2007).

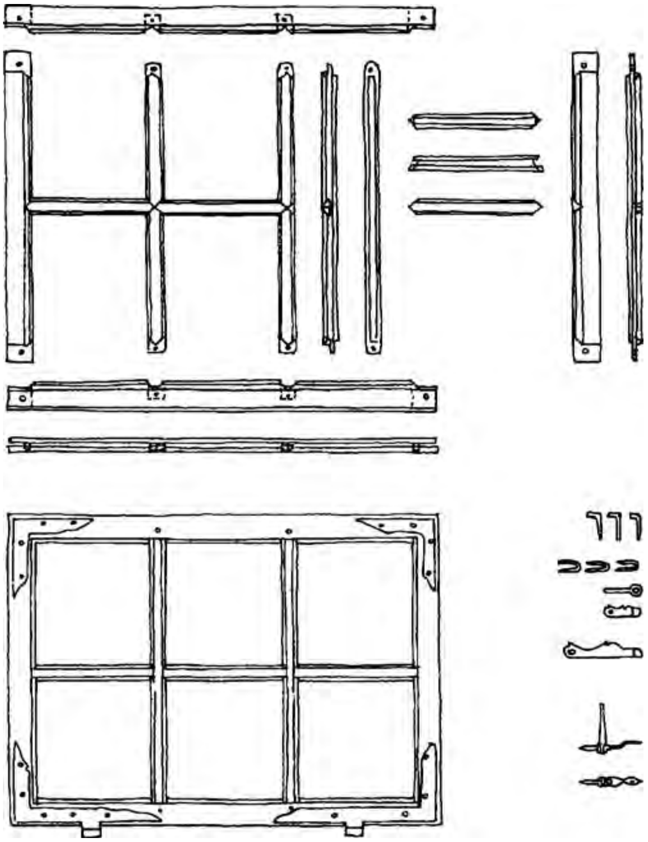
16.1.2 Timber windows

Timber frames used to be made of high quality timber with no knots – often pine heartwood. When constructing the window, the highest quality was selected for the most exposed parts, such as the sill. The components were slotted together and fixed inside with wooden plugs. These days, windows are still generally made of pine, but without the same demands on quality or preparation. Also, the proportion of heartwood used is often very low. To compensate for this, it is quite common to use pressure-impregnated timber, or to use aluminium cladding on the most exposed window parts. Adhesives or screws are used as a binder between the components. The window fittings and the hinges are usually made of galvanized steel or brass. Between the frame and the casement in windows that open there is a weather strip – usually made from polyurethane or ethylene propylene rubber, although it can also be made from silicone rubber, polyvinyl chloride, butyl rubber and chloroprene rubber. Strips of woven wool and cotton are probably the most robust. These products can, however, contain biocides.

Timber windows are mainly based on renewable resources. The energy consumption in the production phase is low, as are the levels of pollution. Pressure impregnation, weather strips of plastic and metal furniture reduce this advantage. Timber windows are well-suited for local production and create few problems in a building, except for potential emissions from some impregnated timber.

Old quality timber frames have been known to last for 250 years under favourable conditions. Until the middle of the twentieth century, a timber window was considered to have a lifespan of 50 years. However, since the 1960s, the rotting of timber windows has increased considerably. In many cases, serious damage has occurred 10 or 15 years after installation. Sweden's State Testing Station has registered that linseed oil and alkyd oil paints give timber the best durability (Phil, 1990).

Timber windows of high quality are usually well-suited for re-use (Figure 16.3). Cleaning, repairing and repainting an old window amounts to approximately 80% of corresponding new production costs (Lauritzen *et al.,* 1991). Older windows usually need a new sill; in some cases turning the window upside down so that the previously exposed parts rest further up is sufficient. The recommended way to remove old paint is to use a blowtorch; however, the vapour from a blowtorch can cause acute allergies. Treating the paint and timber with acid or soda is also possible, but this is often quite aggressive to the wooden material. Metal ironmongery and furniture can often be re-used or recycled. Pure timber waste can be energy recycled in normal incinerators. Impregnated timber and plastic materials have to be incinerated at high temperatures with flue gas cleaning or dumped at controlled tips.



16.2

Traditional window construction for single-glazed windows.
Source: Jessen, 1975.

THE SUSTAINABLE WINDOW

The modern sustainable window (Figure 16.4) is manufactured as a three-layered, coupled window, where the middle and best protected pane of glass is a low energy glass with a coating of metallic oxide. By having this in the middle there is less chance of dust settling on the film, which would reduce the effective saving of energy.

The outer glass is held in place with linseed oil putty and the two inner panes are fixed on strips of untreated wool. The outside layer of the window is the part most directly exposed to the outdoor climate including burning sun and driving rain. The outside frame in a sustainable window is therefore designed so that it can be easily replaced, and the casement has smaller panes of glass in case of breakage. The sill is made from mature oak or pine heartwood. During the summer, the two inner window frames can be removed to improve the transparency of light to the interior. The window is fixed to the building structure with screws.

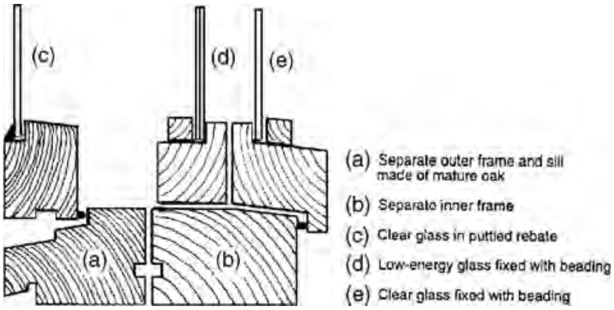
16.1.3 Timber doors

Different types of timber can be used for doors: pine, spruce, oak, beech and birch, either as solid wood or as veneer. There are two main construction techniques for doors: framed and panelled doors and flush doors, both of which are built up with a solid timber frame. Both types usually have sealing strips as well as hinges, door handles, housing for the locks and other ironmongery.

16.3

Re-use of windows in a semi-climatized room in Krinkelkroken kindergarten, Trondheim (Norway). Architects: HSØ Arkitektkontor AS, 2000.

Framed and panelled doors are built with a wide timber frame (Figure 16.5). This was traditionally fixed together with wooden plugs, but nowadays it is glued. In the spaces between the frame, solid timber panels are placed, or panels of chipboard, plywood, hard fibreboard



16.4

The principle section of a sustainable window construction. Gaia Lista, 1995.

16.5

A framed and panelled door.

or even glass. These are slotted into the groove on the inside of the frame. To stop the frame bending, it is usual to split it into two, turn half of it through 180° and glue it together again. This lamination is not necessary for internal doors between dry rooms.

This type of door has poor thermal insulation properties and is usually used internally. Two such doors with a porch in between, however, should give a good internal thermal climate in most conditions.

Flush doors also have a frame, but not as large as the frame of a panelled door (Figure 16.6). A flush door is stiffened by thin layers of board, fibreboard or plywood, fixed with adhesive or pins on both sides. External doors must use a water-insoluble adhesive. Thermal insulation can be placed in the space between the layers of fibreboard, such as expanded polystyrene, mineral wool and porous fibreboard, woodwool slabs, wood shavings, etc. For light doors it is usual to add a sound insulating layer of corrugated cardboard or layers of interlocking wood fibre bands, a waste product from the wood fibre industry. In fire doors, non-flammable sheets of plasterboard or other mineral materials are inserted. A flush door can also have glazing, but glazing will need its own frame.

Common adhesives used in door manufacturing are phenol-resorcinol-formaldehyde (PRF), phenol-formaldehyde (PF), polyvinyl-acetate (PVAC) and polyurethane (PU) (see Chapter 17). Casein glue, animal glue and soya glue can also be used. Doors are often delivered ready to mount, so they have either a polyurethane varnish or an alkyd or linseed oil painted finish.

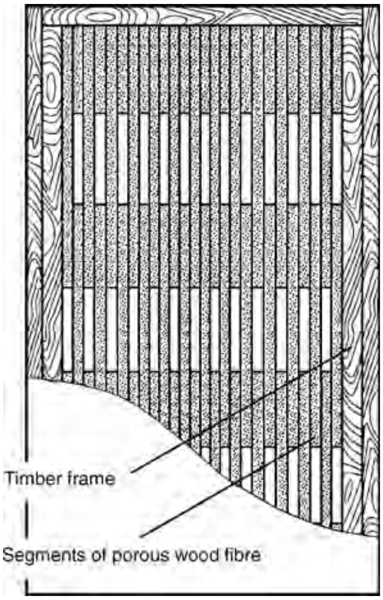
The environmental aspects of timber doors are good, but it is quite clear that the choice of insulating material, glued boards, sealing strips, surface treatment and ironmongery all play their part in production consequences and have potential effects on the internal environment.

Doors can often be re-used, especially robust, solid framed and panelled doors. It is also an advantage if the door leaf can be dismantled with the doorframe intact. The manufacture of a new doorframe can be expensive, especially if its dimensions are not to the current standard. This assumes that the doorframe was originally fixed for simple dismantling, preferably with screws.

Defective doors of solid timber can usually be energy recycled or composted, but laminated products have to be deposited at special tips, or burned for energy recovery in incinerators that clean the fumes.

16.1.4 Plastic and aluminium windows and doors

Window frames of plastic and aluminium usually consist of profiles filled with thermal insulation of foamed polyurethane or polystyrene. Some products use aluminium and timber, where timber is the insulating and structural material. Lower quality timber can be used, as the outer layer of aluminium protects against climate exposure. Aluminium products are usually coated with a thin polymer powder coating. Plastic windows are usually made of hard polyvinyl chloride (PVC) stabilized by cadmium, lead and tin compounds and with added colour pigments. A structural core of steel is always used. In recent years, window frames made from specially developed plastic composites have also appeared which have less heat loss than both aluminium and PVC.



16.6

A flush door.

Plastic and aluminium products have a very limited reserve of raw materials, and pollution during processing is considerable. The manufacture of an aluminium window uses 6 to 10 times more energy input than a timber window; a window of PVC uses about 3 times more and a wooden window with aluminium cladding approximately 50% more.

The lifetime for PVC windows will be shorter than for aluminium ones. This is mainly due to their sensitivity to temperature changes and ultraviolet radiation. However, if not protected well by coatings, aluminium gets easily damaged under corrosive conditions especially in coastal and industrial areas.

Many aluminium and PVC window frames are assembled in situ and likely to fall to pieces when removed. But both plastic and aluminium windows can be re-used if they are initially installed for easy dismantling. Pure aluminium windows can be material-recycled. This is unlikely for the other products, as they all contain complex combinations of different materials. Waste has to be deposited at special tips. From combustion of PVC dioxins and heavy metals can be emitted. Special care for disposal of the ash must be exercised.

16.2 STAIRS

Stairs are, in a way, a specialized part of the floor. The main materials used are timber, stone, brick, concrete and cast iron. The steps have structural requirements and must, at the same time, provide a comfortable underlay for the foot. Common finishes include linoleum and ceramic tiles.

TYPES OF STAIRS

Wooden stairs of non-impregnated timber are used mainly indoors, but they can also be placed outside if they are under shelter (Figure 16.8). Pine, oak, ash, beech and elm are hard-wearing materials and can often be used with a treatment consisting of soap or linseed oil. The timber should be of a high quality and should not have any knots. Handrails and banisters can be made of maple, which has a smooth surface well suited for this purpose.

It has become common to use laminated timber in recent years. Here phenol-resorcinol-formaldehyde glue (PRF) is widely used, but casein glue is also suitable. Outdoor wooden stairs are often treated with fungicides.

Stone stairs are particularly well-suited for outdoor use. Stones can be used direct from the quarry, or cut. Granite is the most hard-wearing variety. It is also possible to use pieces of quartzite slate for the steps. It is usual to have a forged iron balustrade with natural stone stairs. This is set in pre-bored holes with floating sulphur. The sulphur solidifies in a few minutes and prevents any rust getting to the foot.

Brick stairs can be used inside and outside and are usually built from ordinary bricks. For outdoor placing vitrified bricks should be used.

Concrete stairs can be used inside and outside. Uncovered concrete stairs have a tendency to get dusty. It is normal to cover them with ceramic tiles or terrazzo.

Cast iron and steel stairs came into use in late nineteenth century and are often used for fire escapes. They are usually galvanized or painted.

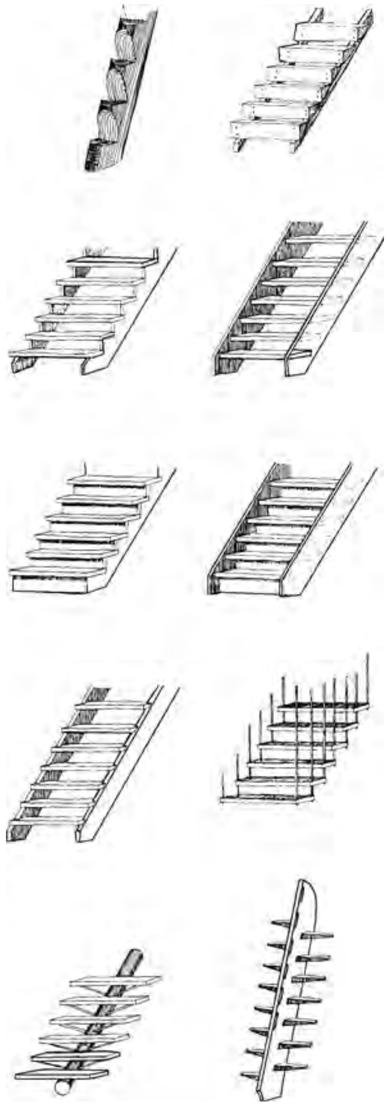
16.7

The door of a lap cottage with a protective layer of birch bark fixed with branches of bracken.

Wooden and stone stairs use the most favourable raw materials, environmentally speaking. They also have low levels of pollution and energy use in production.

Within a building, stairs have practically no side effects. Exceptions that can lead to polluting emissions are impregnated wood stairs, and some paints used both on iron and wooden products. Steel stairs and reinforced brick and concrete stairs can increase the electromagnetic fields in a house.

All types of stairs have a re-use potential, especially wooden stairs mounted in modular parts for simple dismantling, dry stone stairs, brick stairs laid in a weak mortar, standardized steel stairs, etc. Certain prefabricated concrete stairs are also suitable for re-use. Products cast in situ can be recycled as fill or aggregate for low quality concrete work. Steel products can be easily recycled through smelting.



16.8

Constructions for wooden stairs.

Stone, brick and concrete are inert and relatively problem free as waste. Impregnated timber must be deposited at special dumps or incinerated at high temperatures with special cleaning equipment.

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17 Fixings and connections

All materials and components in a building have to be fixed, using either mechanical or chemical means. Mechanical fixings include nails, pins or staples, screws, bolts and wooden or iron plugs. Chemical fixings bond materials together when set. These can be divided into adhesives and mortars.

DECONSTRUCTION AND RECYCLING

The method of fixing very largely determines to what extent a product can be disassembled for re-use, material recycling or energy recovery. Mechanical connections are clearly preferable. Components fixed with adhesives or mortars will, in many cases, be difficult to disassemble; that may also require onerous cleaning.

When mechanical connections are used, notching and holing should be avoided where possible and fixing free zones should be a part of the design to maximize the re-use value of components.

17.1 MECHANICAL FIXINGS

Even though forged iron has been known in Northern Europe since 1000 AD, neither iron nor steel were extensively used as a building material until the industrial revolution. Houses were built in earth, stone, brick and timber. The three first materials were fastened together with simple mortars, whereas timber components which were to be lengthened, strengthened or connected were joined together with locking joints.

A common quality of locking joints is that they reduce the strength of the timber as little as possible. Certain joints are used to preserve the timber’s tensile and bending strength, others to preserve the compressive strength (see Figure 13.28). Wooden plugs used to be an integral part of locking joints, often incorporated with the locks, but their most important role was as fixings for both structure and claddings. These days, nails and screws in steel are the sole components used for the vast majority of mechanical fixings in timber building. Steel bolts are used in buildings with large structural elements. Fixing products are also made of aluminium, copper, bronze and stainless steel.

A normal-sized timber house will contain about 100 to 150 kg of nails, screws and bolts. Steel structures are joined mainly through welding, but bolts can also be used, as was the case during the nineteenth century, before mobile welding became commonplace.

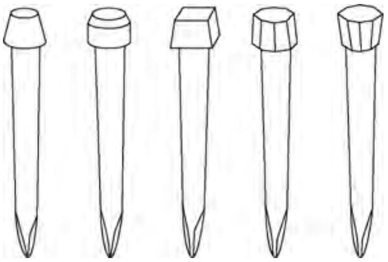
17.1.1 Timber

Joints. Timber joint technology is particularly well-developed in countries like Japan, with a choice of some 600 joint types. In Scandinavia there is a tradition of log construction with 10 to 20 different jointing techniques. In some types of structural framework, such as in the stave churches, grooves are often used to fix external panelling. Nails are not necessary in this form of construction, and where the fastening is part and parcel of the whole structural system it is known as a 'macro-joint'.

Pins and bolts. The use of timber pins and bolts is particularly widespread in areas with early forms of timber frame tradition (Figure 17.1). Pins of juniper, oak and maple are considered the best, although other types of wood can be used. The pins in timber framing are often 15–30 cm long, while pins for fixing and cladding are smaller. Dowels can be executed in such a way that they are slightly larger in diameter than the holes. If they are also drier than the recipient timber component when they are inserted, they will expand later thus locking into place. They are often dipped in water or milk before being rammed in. Alternatively, they can be glued.

There is a lack of steel in India, and wooden bolts are often used as a fixing component in timber structures. The Forest Research Institute in Dehra Dun has researched the strength of wooden bolts and found that they were consistently about 68% as strong as steel of the same size. The timber bolts used in the research had nuts 12 mm in diameter and 100 mm in length. The timber was taken from various trees of normal strengths (Masani *et al.*, 1972). However, timber is simply not as homogeneous as steel and its strength properties are less standardized and difficult to assess. Timber plugs disappeared from the market in Europe during the middle of the nineteenth century as a result of new standards specifying strength properties.

To a certain extent, the use of timber plugs is on its way back into building; for example, in military radar stations where metal components would disturb radio signals. Several massive timber construction systems also use timber dowels. There are guidelines for their production and dimensions. Industrial production of timber bolts and pins is not necessarily less efficient or expensive than for the equivalent steel products (Kessel *et al.*, 1994).



17.1

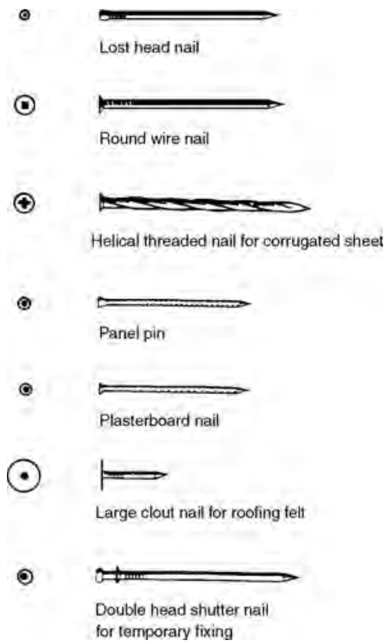
Timber bolts.

Fixings made of timber are based purely on renewable resources. The energy consumption and pollution in the production phase are low. The quality of timber used for jointing, pins and bolts is normally so good that no impregnation is needed.

Durability of the products is also very good. Whilst connections in steel in certain situations can lead to condensation and decay of the adjacent timber, timber fixing components are neutral and stable.

Wooden plugs can easily be sawn off or drilled out for re-use of the structures. Pure timber waste can be burned for energy recovery or composted.

17.1.2 Metal



17.2

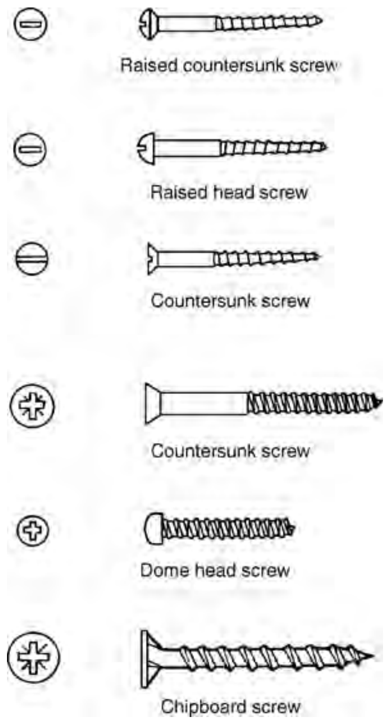
Standard nails.

Nails. There are two main groups of nails: cut nails and wire nails. Cut nails are the oldest and original type and usually have a slight wedge form. They were used in all situations until the end of the nineteenth century, when the manufacture of wire nails began. Wire nails are ubiquitous nowadays (Figure 17.2). In the UK they are round or oblong; in Scandinavia they usually have a square cross-section with a pyramidal tip. Galvanized nails are used on external surfaces to cope with recurring dampness. They are also used internally, where galvanizing is usually unnecessary.

Gangnailplates are made for fixing larger components together, such as the timbers within a roof truss. The gangnailplate is a galvanized steel sheet punched to form many nails, which makes a good fastening and prevents the timber from splitting.

Screws draw themselves into the timber as they are turned, and are used in finer joinery work, ironmongery and internal detailing (Figure 17.3). The work is more demanding than nailing, but screws damage the timber far less.

Bolts. Metal bolts are used in connections where strong forces are to be transferred. Toothplate timber connectors are often laid between structural parts to increase the capacity of a bolt to transfer loads. These connectors have spikes that are pressed into the timber so that the forces are transferred to the surface of friction between the two parts. The bolt's task is thereby reduced to simply holding the two structural parts together.



17.3

Standard wood screws.

Generally speaking, metals have limited reserves. In certain cases scrap metal is used. Energy demand in production is high, and serious pollutants are emitted from the processes. It must be considered as an overinvestment of quality when using galvanized steel products in dry, indoor environments. Untreated steel products have a far better environmental profile.

Metal products do not cause environmental problems in buildings. In a fire, however, they will quickly become red hot and burn through adjacent timber.

The durability of metal products is generally good. If a metal component is exposed to great variations in temperature, condensation can form on it. This has a deteriorating effect on the adjacent timber through electrolytic activity. If timber is damp when a metal component is added, the same effect could occur. Timber impregnated with salt can also corrode metal.

Nails and nailplates have no re-use value, and will probably not be saved for material recycling. Exceptions can occur when demolition material is burnt and metals are cleaned from the ashes. High quality screws and bolts can be retained and re-used or recycled. Use of screwed and bolted connections also means that materials they join together can be easily dismantled and re-used. This is, however, not the case if screw heads are damaged or blocked with filler and paint or if bolts are seized up. Under such circumstances dismantling of nailed constructions can prove to be an easier task. Metals that cannot be recycled should be deposited at special tips.

17.2 CHEMICAL BINDERS

Mortars, adhesives and fillers are important materials in the building industry. Mortar and adhesives are used to bind together different or similar components; fillers are a subgroup used to fill cracks while sticking to the surfaces that surround them. Fillers differ from putty in that they harden and do not retain any elasticity.

17.2.1 Mortars

A mortar is usually a mixture of lime or cement with sand and water, often with additional pozzolanas and accessory agents added, used as a binder for different types of mineral building components: slabs, tiles, bricks, blocks and in certain circumstances roof tiles (Table 17.1). Mortars can also be based on gypsum, clay and sulphur. Fine or coarse sand is used as aggregate, according to the smoothness of finish required. In lime mortar, fine sand is usually chosen, preferably beach sand where the salt is washed out. Successful trials have also been made with mortars using a portion of crushed recycled glass which also has pozzolanic properties (Fragata, 2007). Small amounts of fibre can be added to increase the strength of the mortar. Mineral fibres or organic alternatives such as hemp, sisal, jute or animal hair can be used. Fine aggregates of granulated and foamed recycled glass, perlite, vermiculite or similar materials can also be added to increase the thermal insulation value. In certain modern mortar mixtures extra additives provide elasticity, watertightness, etc.

Table 17.1 *Mortars in masonry*

Mortar	*Mixtures, parts per volume*	*Properties*	*Areas of use*
Lime	Lime 1; Sand 2–3	Elastic, medium strength, sensitive to moisture/frost, quick-drying	All types of internal masonry; brick floors
Hydraulic lime	Hydraulic lime 1; Sand 2–4	Elastic, medium strength, frost-resistant, quick-drying	All types of internal and external masonry; brick floors
Anhydrite and gypsum	Gypsum 1; Sand 1–3	Elastic, weak, sensitive to moisture/frost, quick-drying	Internal masonry
Portland cement	Cement 1; Sand 3–4	Less elastic, low moisture diffusivity, frost-resistant, quick-drying	Internal and external tiling
Lime Portland cement	Lime 1–2; Cement 1–2; Sand 7–11	Elastic, medium strength to strong, frost-resistant, quick-drying	All types of internal and external masonry
Sulphur	Sulphur	Elastic, medium strength, moderate resistance to moisture/frost, watertight	Walling of sulphur blocks and bricks
Clay	Clay 5; Sand 1	Elastic, weak, sensitive to moisture/frost, quick-drying	Walling of earth blocks (adobe) and low-fired bricks

Aggregates must not react chemically with any other materials in the mortar, nor take an active part in the solidifying or curing. Water used in lime and cement mortars should be fresh and must not contain salt, sulphur or other substances that can break down the mixture.

Blocks or bricks are usually laid with mortar joints. But a fibre-reinforced mortar can also be sprayed on both sides of a wall built completely dry (see Figure 13.4).

Mortars have different elasticity coefficients and strengths. This is critical for the tasks they perform, but is also important for any later dismantling of components. Pure Portland cement mortar is, for example, twice as strong as pure lime mortar; hydraulic lime mortar is somewhere between these. The use of lime mortars, hydraulic lime mortars and lime-cement mortars rich in lime makes it quite easy to dismantle walls of bricks and concrete blocks for re-use. They are also more tolerant to movements due to thermal and moisture action. Lime-based mortars are also capable of self-healing of microscopic cracks by plastic flow and diffusion (Yates *et al.*, 2007).

Mortar products are based mainly on materials with rich reserves. The energy consumption in production is considerable; as are emissions of carbon dioxide, nitrogen oxides, sulphur dioxide and dust. The environmental load is less for mortars rich in pozzolanas or based on lime and hydraulic lime than for mortars based on Portland cement. Lime mortars will also subsequently reabsorb more of the carbon dioxide emitted during production than is the case with Portland cement mortars.

Mortars were once entirely mixed on site with local aggregates; it is more normal these days to use ready-mixed mortars. Centralized production means an increased use of transport energy, since even the aggregate has to be transported great distances. However, the aggregates used are often light and give better thermal insulation in the finished structures.

Mortars cause no problem once in place, as long as no volatile organic compounds have been added.

Sulphur mortars can be recycled. This is also true for pure lime mortars, in theory, because they can be re-burned, but this is difficult to achieve in practice. Most mortars can be ground into aggregate for low quality concrete structures.

As waste, mortars are normally inert and can be used as fill. Ground lime mortars can be used for soil improvement. Sulphur pollution can develop from gypsum waste because of microbial decomposition. Sulphur waste should be deposited at special dumps, preferably neutralized by adding lime.

17.2.2 Adhesives and fillers

Adhesives are usually divided into mineral, synthetic, animal and plant products (Table 17.2). Fillers are produced in the same way as ordinary adhesives and mixed in with powdered stone, fossil meal, wood dust, chalk, perlite and similar substances.

Archaeological exploration indicates that animal glue adhesives were in use as far back as 3000 to 4000 BC. In China and Egypt casein glue was used in finer joinery. Somehow this knowledge disappeared, but

Table 17.2 *Adhesives used in building*

Type of adhesive	*Main constituents*	*Moisture resistance*[1]	*Areas of use*
Mineral adhesives:			
Cement adhesive	Portland cement; stone dust, possibly acrylates; water	5	Fixing of ceramic tiles and aerated concrete blocks
Waterglass adhesive	Waterglass; lime; stone dust; possibly acrylates; water	4	Fixing of ceramic tiles; bonding of wood fibreboards, chipboards and fillers
Synthetic resins:			
Acrylate adhesives	Acrylates (butylacrylate etc.); water; organic solvents[2]	5	Fixing of timber; plastics; ceramics; carpets; linoleum; fibreglass; bonding of fillers
Chloroprene rubber CR	Chloroprene; organic solvents; softeners	5	Fixing of plastics
Epoxy adhesive EP	Epoxy; amines; polyamide	5	Fixing of stone; glass; metal; plastic; ceramic tiles; binder in fillers
Ethylene vinyl acetate adhesive EVA	Ethylene; vinyl acetate; water; organic solvents[2]; softeners	5	Fixing of plastic sheeting and linoleum
Isocyanate adhesive EPI	Isocyanates; styrene-butadiene rubber or polyvinyl-acetate; water	5	Bonding of timber, plywood; fixing of metals
Melamin-urea-formaldehyde MUF[3]	Melamin; urea; formaldehyde	4	Bonding of timber and wood fibreboards
Melamin-urea-phenol-Formaldehyde MUPF[3]	Melamin; urea; formaldehyde	4	Bonding of timber, wood fibreboards and particle boards
Methylene-diphenyl-isocyanate MDI	Methylene-diphenyl diisocyanate	4	Bonding of particle boards
Phenol-formaldehyde PF[3]	Phenol; formaldehyde	5	Bonding of mineral wool, wood fibreboards, chipboards, plywood and cork tiles
Phenol-resorcinol-formaldehyde PRF[3]	Phenol; resorcinol; formaldehyde	5	Bonding of timber and plywood
Polyurethane adhesive PUR (1 or 2 component)	Polyurethane or isocyanates and polyols	4	Bonding of timber, wood fibreboards, particle boards, cork tiles, strawboards; fixing of wood, metal and plastics
Polyvinyl-acetate adhesive (PVAC)[4]	Vinylacetate; water; organic solvents[2]; softeners	3	Bonding of timber and fillers; fixing of soft floor coverings, wallpaper, wood products
Silicone rubber Si	Silicone; organic solvents	4	Fixing of timber, metals, plastics
Styrene-butadiene rubber SBR	Butadiene; styrene; organic solvents; softeners	5	Fixing of timber, mineral sheeting; bonding of carpets
Urea-formaldehyde UF	Urea; formaldehyde; water	3	Bonding of chipboard

Table 17.2 *(Continued)*

Plant-based adhesives:			
Cellulose adhesive	Derivatives of cellulose; organic solvents	5	Fixing of linoleum
Cellulose paste	Methyl cellulose; water	3	Fixing of wallpapers, hessian and linoleum; bonding of fillers
Colophony resin	Colophony; organic solvents	4	Bonding of wood fibreboards
Latex adhesive	Natural rubber; organic solvents	4	Bonding of paper sheeting; fixing of linoleum and timber
Potato flour paste	Potato starch; water	2	Fixing of wallpaper
Rye flour paste	Rye flour starch; water	2	Fixing of wallpaper and linoleum
Soya adhesive	Soya protein; water	3	Bonding of plywood
Sulphite lye adhesive	Lye from waste; water	3	Bonding of wood fibreboards and paper sheeting
Animal glues:			
Casein glue	Milk protein; lime; water	4	Bonding of timber and plywood; fixing of timber
Collagen glue	Protein from tissue; water	3	Bonding of timber and plywood
Blood albumin glue	Blood protein; ammonia; calcium hydrate; water	4	Bonding of plywood

[1] Sensitivity to moisture is divided into a scale from 1 to 5, meaning: 5: For outdoor use. 4: Outdoor use, but sheltered from rain. 3: Indoor use, in relatively dry places. 2: Indoor use, in permanently dry situations.

[2] Secondary solvent.

[3] As these adhesives are most often used as 'hot melts' solvents are less needed. Cold versions may depend on substantial amounts of added solvents.

[4] An alternative version for outdoor use have chromium compounds added.

was rediscovered in Europe around the sixteenth century. The first glue factory was built in the Netherlands in 1690. Around 1875 the manufacture of plywood started, and at the turn of the century laminated timber construction began. Synthetic adhesives came into production around 1930 and today are used across the whole industry. There are now between 100 and 300 different building adhesives available on the market. A normal Swedish home contains about 700 litres of adhesive, when furniture is included.

Fillers only came into use well into the twentieth century when smooth, even surfaces were required.

Mineral adhesives are usually based on Portland cement or waterglass (see page 90) and are used mainly for ceramic tiles, but have also become an adhesive for masonry. They are then used for precision components with accurate dimensions, such as blocks of aerated concrete. The adhesive used is usually a cement glue with a large proportion of acrylates mixed in. The joint is so strong that attempts at dismantling the wall may be difficult without destroying the blocks. Waterglass glue can also provide the base for a filler by mixing it with clay powder.

Mineral adhesives are based on resources with rich reserves. Both the energy used and pollution caused during production are moderate compared to commercial alternatives. Inside a building, products containing acrylates can cause problems for the indoor environment during their curing process. Pure waterglass products create no problems at all. As waste, waterglass glue is considered to be inert, whilst cement-based glue containing acrylates has to be deposited at special tips.

Synthetic adhesives are usually divided into thermosetting and thermoplastic adhesives.

The *thermosetting* adhesives are often called 'synthetic resins' and the binders are usually based on one or more of the compounds urea, formaldehyde, phenol, melamine, resorcinol, acrylic acid, epoxy and polyurethane. Epoxy is composed of epichlorohydrin and bisphenol A, while polyurethane is manufactured from isocyanates. In several products a separate hardener is added in order to complete the gluing process, usually amines, ammonium chloride or polyoxymethylene. Some thermosetting adhesives are soluble in water while others need organic solvents like ethanol and ethylene glycol.

Important thermosetting adhesives are phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF), often used for the laminating of timber. Polyurethane (PUR) and urea-formaldehyde (UF) dominate in the production of chipboards and plywood. Phenol-formaldehyde (PF) is used in the production of matting of mineral wool, and epoxy adhesives to glue a wide range of materials from stone to glass and metals.

Synthetic rubber adhesives produced from chloroprene (CR) and styrene-butadiene (SBR) represent a subgroup of thermosetting adhesives with almost permanent elasticity. They require large amounts of organic solvents that can include aromatics and esters.

Thermoplastic adhesives are delivered ready-made from the factory, often emulsified in a solvent. Important adhesives of this type are polyvinyl-acetate (PVAC), ethylene-vinyl-acetate (EVA) and methyl-metacrylate (MMA). Thermoplastic adhesives are partly soluble in water, partly soluble in organic solvents, most often ethanol or toluene. The dispersion agent nonylphenol was widely used earlier, but is probably substituted in most modern products. Water-based products always have fungicides added, usually isothiazolinone or bronopol. Softeners are also used, most often as butyldiglycolacetate or phthalates.

So-called 'thermal bonding' can be achieved by melting thermoplastic fibres, usually of polypropylene (PP) and polyethylene terephthalate (PET). This is generally not considered as conventional gluing. Thermal bonding is much used for fixing natural fibres in insulation matting.

Thermosetting adhesives are very widespread in the building industry, but they are less relevant as building adhesives on site, except when gluing external components where high strength and resistance to moisture is needed. *Thermoplastic* adhesives are the most common glues used on site. Fillers for indoor use are mainly based on PVAC adhesive.

The synthetic adhesives are based on fossil resources. The production is intensive in energy and a wide range of serious pollutants can be emitted. Within buildings, these products can create problems for the indoor climate through the emission of solvents and other volatile

Table 17.3 *Synthetic adhesives and essential hazardous substances that may be found in production and/or in finished product*

Product	*Substances*[1]
Chloroprene rubber CR	Butadiene; chloroprene[2]
Epoxy	Epichlorohydrin; bisphenol A; amines[2]
Isocyanate EPI	Isocyanates[2]; styrene; xylene; butadiene; hexane[2]; toluene[2]
Melamin-urea-formaldehyde MUF	Formaldehyde
Melamin-urea-phenol-formaldehyde MUPF	Phenol; formaldehyde
Methylene-diphenyl diisocyanate MDI	Methylene-diphenyl diisocyanate[2]
Phenol-formaldehyde PF	Phenol; formaldehyde[2]
Phenol-formaldehyde-resorcinol PFR	Phenol; formaldehyde; resorcinol
Polyurethane PUR	Isocyanates[2]; chlorinated hydrocarbons; amines[2]
Silicone Si	Chlorinated hydrocarbons; xylene[2]; amines[2]; siloxanes[2]
Styrene-butadiene rubber SBR	Styrene[2]; xylene[2]; butadiene; hexane[2]; toluene[2]; amines[2]
Urea-formaldehyde UF	Formaldehyde[2]

See risk potential in Table 2.5.

[1] Additional substances may well occur. Production of basic ingredients is not included.

[2] Risk of emissions from cured products.

compounds during the curing phase, and sometimes for a longer period, in some cases as a result of ageing (Table 17.3). Waste from hardened and non-hardened adhesives usually requires disposal at special tips, as do glued products, depending upon which adhesive is used and in what quantity. As a whole, PVAC and EVA-glues are the least problematic.

Animal glues are based on substances rich in protein such as milk, blood and tissues, and are divided into three main types: collagen glue, blood albumin glue and casein glue. These are all soluble in water. They are all good glues for wood, and can be used on everything from veneers and furniture to large laminated timber structures. Some glues have fungicides added.

Collagen glues are mostly based on waste from abattoirs and fisheries. Casein glue is produced from milk. Under dry conditions in buildings, the products cause no problem. However, in combination with damp cement, they can emit ammonia that irritates respiratory passages. In continuous damp conditions, there is a chance of mould or other bacteria developing and the rotting products can cause bad odours, irritation and allergies. This can also lead to the deterioration of the building structure. Wastes from the glues are highly eutrophicating, but this risk is insignificant since the amount is usually small. Glues containing potentially damaging fungicides must be deposited on special tips.

Materials glued with animal glue can normally be energy recycled in ordinary incinerators, or can be dumped without any particular restrictions.

COLLAGEN GLUE

Collagen glue is made from the tissues of animals containing collagen, a protein. By boiling it in an evacuated vessel it turns into glue. This is then dried into a granulated powder or made into small bars. *Gelatine* is collagen glue that has been cleaned of colour, smell and taste.

There are three basic types of collagen glue: bone glue, hide glue and fish glue. The first two are often called 'glutin glue'. Bone glue is made from bones and knuckles. Hide glue is made from waste hides from places such as tanneries. Fish glue is made from fish bones and other fish waste. All of these glues are strong, but hide glue is considered the best.

Collagen glue bars or powder can be placed in cold water to soften up and then dissolved in water at 50–60 °C using about two to three times as much water as the weight of softened glue. The powder can also be released directly into warm water. Temperatures above 60 °C decrease the quality of the glue. Bone glue and hide glue have to be used warm and the pieces to be glued must be put under pressure before it stiffens. The glue cures quickly when cooling. Fish glue can be used cold, as can the other collagen glues when calcium chloride is added.

To make a good collagen glue filler for timber surfaces, saw dust or wood flour is mixed in. Colour pigments can also be added. Adding gypsum makes the filler white.

Collagen glues based on bones and hides have been used a great deal for gluing plywood. Right up to the Second World War, these were also dominant in furniture making, and there are still craftsmen who say that the quality then was much higher than that achieved today with adhesives such as urea-formaldehyde (Brenna, 1989).

BLOOD ALBUMIN GLUE

Blood albumin glue is soluble in water. It is prepared from fresh blood or from blood serum which is allowed to swell in water. The glue is made by adding ammonia and a calcium hydrate solution in certain proportions. The objects must be warmed up during the actual gluing. At certain temperatures the protein coagulates, and the glue joint becomes totally watertight. The joints have a risk of being attacked by mould and should be kept dry, if fungicides are not added.

CASEIN GLUE

Casein glue was used by craftsmen in ancient China. It is made from skimmed milk. The milk is warmed and rennet is added to separate out the casein. The casein is then dried and mixed with 2.5% (by weight) lime. The powder is mixed with three times as much water, so that the lime is slaked. A glue is then produced which, after setting, tolerates humidity better than collagen glue. However, in permanently damp surroundings, and with timber at more than 18% moisture content, the glue can be attacked by micro-organisms.

Casein glue can be used for internal loadbearing structures, stairs, plywood, laminated timber, etc. without fungicide. However, it is seldom used nowadays. Producers of laminated timber prefer adhesives that can be used in all situations, and therefore choose synthetic resins which have a higher resistance to moisture. Strengthwise, casein glue is as good, and there is proof of its long-lasting qualities in structures that have kept their strength for more than 60 years (Raknes, 1987). A very impressive example can be seen in Stockholm Central Station, where enormous laminated timber arches have been put together with casein glue. During the Second World War, casein glue was used in the manufacture of fighter planes ('Mosquito').

There is a need for the renaissance for environmentally-friendly casein glue. This does not necessarily conflict with economic considerations: it has been shown that casein glue can be produced for less than 25% of the cost of synthetic alternatives.

Plant glues include soya glue, natural resin glue and cellulose glues as well as glues based on rye flour and potato flour.

Lignin is a natural resin that is found in some quantity in all plant material. It separates out under heating, normally with the help of small amounts of aluminium sulphate. In many hard and semi-hard plant-based board materials it is therefore unnecessary to add other adhesives. The addition of laccase enhances this process to the extent that a wider spectre of product types can also be made without added glues (Lund, 2003). Another natural resin is colophony which is extracted from coniferous trees and used with additional solvents, mostly turpentine distilled from wood tar.

Soya glue is a water-based protein glue taken from the waste products of cooking oil production. Glues produced from cellulose are available in both water and solvent-based variations. The organic solvents used are most often turpentine or pure alcohol, the latter up to as much as 70%. The water-based cellulose glue is usually called *paste*, and is used for putting up wallpaper. Paste can also be made from potato starch or rye flour in water-based solutions. Cellulose adhesives are not attacked by micro-organisms, even in damp conditions. Soya glue and flour paste are more vulnerable and should be restricted to use in dry places.

Plant glues are all based on renewable resources. The products usually cause little pollution in their manufacture, one exception being cellulose glues which are based on methylcellulose. Their production involves the use of chlorinated hydrocarbons such as methyl chloride, methyl iodide and dimethyl sulphate. Another exception is products containing colophony, which is a well-known allergenic substance.

During building use, plant glues do not generally cause problems. Waste from glue can cause the growth of algae in water systems, but this risk is insignificant as the amount of glue in question is usually small. Glues with highly toxic fungicides added are an exception to this. Materials glued together with plant glue can usually be energy recycled in normal incinerators or deposited without special restrictions.

STARCH GLUE

Starch glue or carbohydrate glue is based on vegetable starch. The paste is relatively weak and is used primarily for pasting paper and wallpaper, but it can also be used for lighter woodwork and is used in the USA for gluing plywood. Potato flour paste and flour paste are starch glues.

Potato starch is dissolved in warm water and mixed to a porridge. The porridge is allowed to stand for 10 minutes so that the water is absorbed by the grains of starch and thickens. Afterwards cold water is added to make it easy to stir. The mixture is then boiled to thicken it more; water is added until a workable consistency is obtained. The glue must not be used until it is cold. If the paste has to stand for a time a little alum is added to prevent it turning sour. If hydrochloric acid is added to the potato starch, dextrine is formed, which gives a glue of a far higher durability. Dextrine is also used in fillers containing gypsum.

Flour from wheat, maize or rye is used to make flour paste, which is stirred in warm water to a white sauce, adding water carefully so that the paste does not become lumpy. The mixture can also be sieved. This glue must be used cold, and it is a definite advantage to add alum. Paste from wheat flour is mostly used to stick paper and wallpaper. Rye flour paste is a little stronger and is used for sticking paper on hessian, linoleum and wallpapers, and as a filler. Sago flour is used for the gluing of wood. In commercial products, fungicides are often added.

RYE FLOUR FILLER

An emulsion filler based on rye flour is made from 1 part boiled linseed oil, 1 part of water and about 1 part chalk. This is gently mixed and allowed to stand for half an hour without being stirred. A pinch of rye flour is sprinkled on the mixture and thoroughly stirred in. More chalk, which acts as the filler, is added, until the mixture has the consistency of porridge. Pigments such as umber and ochre can be used to colour it.

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18 Paint, varnish, stain and wax

Paints, varnishes and stains are used to make a building more beautiful. Traditional painting has, to a great extent, revealed a wish to imitate other more noble building materials. The light yellow and grey façades have imitated light stone façades of marble, lime or sandstone; dark red façades have imitated brick. Colour has in this way had an outward-looking, representational function and still is a powerful form of visual communication in most cultures (Ojo *et al.*, 2006). But it can also be used for internal therapy. Theo Gimbel (2004) believes that colours can start a chemical process within us, and that each cell is a sort of eye that takes them in. *Red* helps relieve tiredness and bad moods, but should be avoided by those with heart problems. *Yellow* stimulates the brain. *Green* has a quieting effect, while *violet* strengthens creativity and spirituality. Perception psychology has also shown that experience of space can be manipulated with colours and textures. A correct colouring can 'expand' a small room. This is achieved primarily by using matt finishes in 'receding' colours such as green, blue and blue-grey mixed with white. By contrast, 'advancing' strong colours such as red, yellow and browns will make the room seem smaller. The interplay of surfaces can also have significant effects. A light ceiling in a room with dark walls will 'raise' the room height, and the opposite will make the room feel lower (Neuffert, 1975). In this way, small buildings can be made to appear and feel larger. This might be one way to make reduced space use more acceptable; we know that efficient space use is one of the keys to reduced energy use and environmental impacts of buildings (see page 8).

Paints are also intended to protect the material underneath it. This is not always the case: there are many examples of damage caused by surface treatments, such as render and masonry that quickly begins to decay after treatment with vapour-proof paint, or timber that is often attacked by mould soon after being painted. Research has shown that the decay of untreated timber, when exposed to ultraviolet radiation, wind and rain, is relatively small. In very exposed areas, only about 1 mm is worn down in 10 years; in normal weather conditions 1 mm is eroded in 10 to 100 years. A much more significant protection than even the most careful painting can be obtained instead by working wisely with untreated materials and what is now termed the structural protection of materials (see page 411).

UNTREATED TIMBER CLADDINGS

If a timber façade is left untreated, after a couple of years it will oxidize and develop an even grey tone (Figure 18.1). The process requires that it is evenly exposed to rain; roof overhangs and protruding flashings create a ‘rain shadow’ and in some cases areas where water drips, resulting in uneven colouring. On the other hand, this can be avoided by choosing different materials for surfaces that are not exposed, or else by treating the wall with iron vitriol (see page 404).

An untreated timber cladding will have approximately the same lifetime as one that is painted (Godal, 1994). At the same time, one saves work, expense and the environmental affects arising from cleaning and repainting. In addition, the untreated cladding will be fully biodegradable and ready for energy recovery without the need for special smoke filtering.

The most relevant justification for painting a house is aesthetic. Exceptions are internal surfaces such as floors, mouldings and other details where treatment with oils and waxes will ease cleaning and reduce wear. Colour can also be used to lighten interiors and reduce the need for artificial lighting. Of importance here is wood panelling which, with the exception of aspen, lime and the sapwood of ash, will darken with time. Special paints are used for protection against rust, as flame retardants, as internal vapour barriers, to protect against radon emissions from radioactive building materials, to prevent emissions of volatile formaldehyde from chipboard, etc.

Ordinary paints consist of binders, pigments and solvents. The *binder* is the ‘body’ of the paint, helps the coat of paint to retain its structure, and binds it to the surface to which it is applied. The *pigment* gives the paint colour, but also plays a role in its consistency, ease of application, drying ability, durability and hardness. The *solvent* dissolves the paint to make it usable at normal room temperature and gives ease of penetration in to the surface material. In addition, it is possible to add fillers. Some paints also need a proportion of additional additives in order to fulfil technical and aesthetic requirements; for example, fungicides, drying agents, softeners, etc.

Dispersion paint contains particles so small that they are kept suspended in water – this is known as a ‘colloidal solution’. *Emulsion paint* is a dispersion paint consisting of finely divided oil made soluble in water by adding an emulsifying agent, usually a protein. *Lazure* is paint with less pigment, used when the structure of the material needs to remain visible. Lazure painting can be achieved by using a larger proportion of solvent in the paint. *Varnish* is a paint without pigment, while *stain*, in its classic sense, is a paint with no binder, where the pigment is absorbed directly into the surface. Stain is nowadays often referred to as lazure. The terms used here are the classical definitions. *Wax* and *soap* are also included in this chapter. They have nothing to do with painting, but are widely used in the treatment of wood surfaces, and do have some effect on its appearance. They also saturate the wood so that dirt and moisture cannot get into it.

18.1

Unpainted and naturally grey timber cladding in a harsh climate on the Norwegian coast. Gaia Lista, 2004.

The necessary qualities of paint, varnish, stain and wax are that they must:

- bind well to the surface
- not crack or flake off
- be elastic so that they can tolerate movement in the building.

Table 18.1 *Types of surface treatments*

Type/binder[1]	*Solvent*	*Primary additives*[2]	*Exterior use*	*Interior use*
Cement paints	Water	Possibly dispersing agents	x	x
Lime paints	Water		x	x
Silicate paints	Water	Possibly dispersing agents	x	x
Acrylate paints/varnishes	Water and/or organic solvents	Fungicides, softeners, drying agents, dispersion agents, film-forming agents, etc.	x	x
Alkyd oil paints/varnishes	Organic solvents	Fungicides, drying agents, dispersing agents, skin preventers, etc.	x	x
Epoxy paints/varnishes	Organic solvents	Fungicides; softeners, etc.	x	x
Polyurethane paints/varnishes	Organic solvents	Softeners etc.	x	x
Polyvinylacetate PVAC paints	Water and organic solvents	Softeners[3], fungicides[4]; drying agents; dispersion agents; filmformings agents, etc.	x	x
Collagene glue paints	Water	Possibly fungicides[4]		x
Casein paints	Water	Possibly fungicides[4]		x
Linseed oil paints	Organic solvents	Drying agents; fungicides[4]	x	x
Emulsions of linseed oil with animal glues, starch, etc.	Water	Possibly fungicides[4]	x	x
Wood tar	Organic solvents	Possibly fungicides[4]	x	
Natural resin varnishes	Organic solvents		x	x
Starch paint	Water	Possibly fungicides[4]		x
Cellulose varnishes	Organic solvents		x	x
Cellulose paste paints	Water	Possibly fungicides[4]		x
Chemical stain	Water	Reactive substances	x	x
Water stain	Water		x	x
Beeswax	Organic solvents			x
Green soap	Water			x

[1] Combining binders is possible; for example polyurethane/acrylates.
[2] Excluding pigments.
[3] A co-polymer of PVAC and acrylates do not need additional softeners.
[4] When exposed to moisture.

Special conditions are often required by the materials and components to be treated, and in relation to their position in a building (Table 18.4). Especially important are factors such as diffusivity to moisture, sensitivity to water and mould growth, resistance to wear, sensitivity to light and the risk of emissions. There is a big difference between interior and exterior treatment in this respect.

Of all building materials, surface treatments are those that are renewed most often. The accumulated environmental loads through

Table 18.2 *Synthetic paints and varnishes and essential hazardous substances that may be found in production and/or in finished products*

Product	*Substances*[1]
Acrylate paints/varnishes	Acrylonitrile[2]; acrylic acid[2]; xylene[2]; isothiazolinone; folpet; bronopol; phthalates; styrene[3]; methyl metacrylate
Alkyd oil paints/varnishes	Xylene[2]; toluene[2]; nonylphenol; zinc; folpet; methyl ethyl ketone
Epoxy paints/varnishes	Epichlorohydrin; bisphenol A; amines[2]; xylene[2]; toluene[2]; butanol[2]; methyl isobutyl ketone[2]; phthalates[2]; nonylphenol
Polyurethane paints/varnishes	Isocyanates[2];chlorinated hydrocarbons; amines[2]; toluene[2]; xylene[2]
Polyvinylacetate paints	Phthalates[2]; isothiazolinone; folpet; bronopol

See 'Risk potential' in Table 2.5.

[1] Additional substances may well occur. Production of basic ingredients are not included.

[2] Risk of emissions from treated surface.

[3] In paints for exterior use.

a building's lifetime can therefore be considerable even though the effect of each single treatment may be small (Table 18.3).

Many products for surface treatment are based on raw materials from plants, while other are based on fossil oils. Pigments are usually mineral-based.

The energy consumption in production varies a great deal from product to product and is to a great extent dependent on the choice of pigments and solvents. As a rule of thumb, the surface treatments and their renewal will amount to about 1 to 2% of the total material-related energy requirement of a conventional building over a 50 year period (Baumann *et al.*, 1994).

Table 18.3 *Essential environmental qualities of surface treatments*

Qualities	*Exterior treatment*	*Interior treatment*
As product		
Production from renewable resources	x	x
Low emissions of greenhouse gases and other pollutants in the production phase	x	x
Minimal use of organic solvents and other toxic additives	x	x
Low emissions of organic substances when applied and afterwards	(x)	x
High durability	x	x
High biodegradability as waste	x	x
As part of the treated material		
Maintains the moisture buffer capacity of the underlayer		x
Maintains the surface temperature of the underlayer[1]		x
Maintains the electrostatic properties of the underlayer		x
Maintains the recycling value of the treated material[2]	x	x

Notes: X: of primary relevance.

[1] Most important when used on timber flooring.

[2] Re-use, material recycling and energy recovery.

Table 18.4 *Utility of some low impact paints on mineral materials*

Substrate	*Lime paint*	*Silicate paint*	*Collagen glue paint*	*Casein paint*
Concrete		X		X
Plasterboards			X	X[1]
Lime plaster	X	X[1]		X[1]
Lime sandstone	X	X	X	X
Sandstone/quartzite		X		X
Vitrified bricks				X
Low-/Well-fired bricks		X		X
Loam plasters		X	X	X

Ref.: Ziesemann, 1998.

[1] Subcoating is most often necessary.

In the Scandinavian Products Register for chemical products, there are 11 800 registered paints and varnishes that contain harmful substances. A wide range of pollutants are emitted from the industry. The surface treatments will comprise of a considerable part of the total materials-related emissions of the building. Organic solvents in particular must be included here; they have been estimated to be responsible for about 20% of the hydrocarbon pollution in the atmosphere, second only to the car (Weissenfeld, 1983). Their climate changing potential is three times that of carbon dioxide. Solvents and other constituents in surface treatments can also have significant health effects both for workers and the indoor environment. Amongst both painters and workers in the paints industry there are considerably higher rates of cancer than amongst other groups (Stevenson *et al*., 2007).

Toxic substances can leach from painted façades and pollute surrounding soil and ground water (Andersson, 2002). Inside buildings a whole series of different volatile substances can be emitted from treated surfaces – especially when synthetic products are used – and can have a big impact because they extend over such large areas (Table 18.2)Table 18.1. Besides organic solvents, these can include residual monomers as well as additives like softeners and fungicides. Many of them are environmental toxins; others can lead to irritation in the respiratory system. Emissions often continue several months after the work is completed. As a general rule the thicker the layer of paint or varnish, the longer the time taken for the emissions to complete.

Surface treatments that are less permeable to vapour can also reduce the indoor air quality by blocking the moisture-buffering properties of the building materials treated (Table 18.5). This can imply higher ventilation requirements and energy use. Varnishes will also make floors ‘colder’ since they are good thermal conductors which can make it necessary to have higher room temperatures in buildings such as kindergartens. Certain surface treatments can also become quite heavily electrostatically charged, which can make cleaning more difficult as well as increase the electrostatic charge of the inhabitants (see Table 15.3).

Table 18.5 *Vapour diffusion resistance of paints with thickness 0.05 mm*

Surface treatment	*Vapour diffusion resistance (Z_p) (10^9 m^2sPa/kg)*
Cement paints	0.4
Lime paints	0.2
Silicate paints	0.2–1.0
Acrylate paints/varnishes	0.7–2.7
Alkyd oil paints	2.5–5
Alkyd oil varnishes	19–39
Epoxy paints	40–50
Epoxy varnishes	39–72
Polyurethane varnishes	50
Collagen glue paints	0.2–0.3
Linseed oil, not pigmented	0.9–1.0
Linseed oil paints	1.0–3.5

Lower values indicate an increased potential for utilization of the moisture buffering capacity of the underlayer.

When surface treatments are applied, a mixing of materials occurs that is almost irreversible. Materials that have had surface treatments are therefore not easily recycled. Exceptions include treatments that are easy to clean off (such as collagen glue paint), or where the treatment is similar in composition to the underlay (for example, cement paints on concrete). The same principle applies to the potential for energy recovery and the problem of waste. Painted materials often have to be treated as special waste. As waste, the pigments have the greatest impact since they can contain heavy metals.

PAINTS IN HISTORY

Surface decoration has been popular throughout the ages. Stone Age cave painters used paints based on binders of fat, blood and beeswax, using chalk, soot and different earth colours as pigments. Similar paints were also used for Egyptian fresco paintings about 5000 years ago. Old Hebrew writings describe how casein was stored in the form of curd until the annual visit of the painter during the autumn; at harvest festivals, everything should be newly painted. In Pompeii, paint mixtures of chalk, soap, wax, pigment and water have been found.

It is generally assumed that the exterior of timber buildings remained untreated up to the late Middle Ages. However, as wealthier citizens began to have panelling installed in their houses at the end of the seventeenth century, surface treatment also became more usual. The first coloured tar paints were introduced at this time. The objective of painting was most often to make timber buildings look like stone or brick. The pigments were expensive, with the exception of the earth pigments red ochre and yellow ochre, which after a while dominated the houses of craftsmen and farmers.

Around 1700, linseed oil came into use. During the nineteenth century many old and new pigments were produced chemically. Painting a house became cheaper, and colours other than red and yellow, such as zinc white, became available to everybody. At this time, everyone had untreated floors, although sand was used for scouring. Floor painting began around 1820. From the middle of the twentieth century, very rapid developments led to latex paint and alkyd paints, based on raw materials of fossil origin.

The nature of the paint trade has changed a great deal over the last 100 years. During the nineteenth century, painters prepared the pigments themselves from raw materials. Even as late as the 1960s, most painters mixed paints themselves, although ready-mixed paints had been on the market since the end of the nineteenth century. These days, everything is industrialized, including parts of the application, particularly for windows, doors and outside panelling.

18.1 CONDITIONS FOR PAINTING

The treatment of a surface should be carried out during a period when the surface is dry, preferably in the summer. The temperature does not matter too much, as long as it is some degrees above freezing. Paints with natural oil binders should not be applied at temperatures under 5 °C. Painting carried out in autumn often seems to last longer than painting done during the summer, probably because the paint has dried more slowly. In hot sunny weather paint can easily crumple, because of tension between the different coats.

It is important to choose the right paint for the right surface. Wood, for example, is an organic material that is always moving, swelling in damp weather, or drying out and shrinking in dry weather, and these properties must be taken into account.

18.2 THE MAIN INGREDIENTS OF PAINT

18.2.1 Binders

Binders must be able to dry without losing their binding power. Many different binders have been used throughout history, including materials such as blood, sour milk and urine. According to a representative of the Norwegian custodian of national monuments, Jon Braenne, many of these 'improbable' paints gave 'amazingly good results' (Drange *et al.*, 1980). Linseed oil and protein glue have been amongst the most popular, with a long tradition, and was in continuous use up to the end of the 1950s. Since then, synthetic resins have arrived on the scene, replacing the 'old faithfuls'. Different types of binders vary a great deal in terms of opacity, lustre, spreading rates and durability.

18.2.2 Solvents

Solvents are used to thin out thick paint mixtures and make them more penetrative; they vaporize from the surface after painting. In certain types of paint, the binder itself is capable of dissolving the paint to a satisfactory consistency, as in the case of cold pressed linseed oil, heated wood tar, etc. A few paints can be dissolved in light oils, such as fish oil, whilst some paints dissolve in water. Many paints, especially newer types, and binders of natural resins and wax, must have an organic solvent added. Alcohol can be used in several mixtures, e.g.

in natural resin varnishes. However, most common are mineral spirits and turpentine.

- *Mineral spirits* are distilled from crude oil. The main constituents of the most common mineral spirits are xylene, butanol, toluene, ethyl acetate and methanol. A special mixture is marketed as *white spirit*, and is now the dominating organic solvent in paints.
- *Turpentines* are distilled from wood tar or pressed from orange peel. Sulphate turpentine is produced from sulphate cellulose. Before crude oil based solvents came on the market at the beginning of the twentieth century only turpentine was available. It is still much used for dissolving natural resins and vegetable oils.

Water is without doubt the optimal solvent, environmentally speaking. The organic solvents have considerable environmental implications. Whilst mineral spirits have crude oil as their source, turpentine is based on renewable plant resources. The energy use in production is also higher for mineral spirits and the solvents emitted have a global warming potential three times that of carbon dioxide. Turpentine is considered climate neutral since emissions are equivalent to the carbon dioxide originally taken up during the growth of the plants used as raw material.

On the building site, vaporizing of mineral spirits represents a major problem and is associated with nerve damage and other serious health problems. Many painters refuse to paint with these solvents. Spirits with less acute emissions are the isoaliphates, which are obtained by boiling crude oil at a specific temperature. The vapour from turpentines is normally even more irritating to the mucous membranes than those resulting from mineral spirits. One constituent, pinene, can cause allergies. There is, however, no proof that long-term exposure to turpentine can have the same chronic effects on the nervous system as mineral spirits.

In freshly painted buildings the solvents release gas for shorter or longer periods depending upon the drying conditions of the building. Solvents vaporize completely, so there are no waste problems.

18.2.3 Pigments

Pigments have to satisfy certain conditions such as opacity, strength of colour and spreading rate, and they must not fade with exposure to light (Table 18.6). Pigments should neither melt nor dissolve in the binders or solvents used in the paint. Not all pigments can be used in all paints; for example, pigments in a lime based paint have to be compatible with lime. White pigment is the most popular and represents about 90% of all pigments used. Pigments can be inorganic or organic. There are two types of inorganic pigments: earth pigment and mineral pigment.

Earth pigment occurs ready-to-use in certain types of earth. It is composed of the decaying products of particular types of stone, and has good durability. Extraction involves washing the earth. Water is added and the mixture is stirred and left. When all of the earth has settled, the water is poured off and the uppermost layer of fine earth is treated in the same way. This is done five or six times. The earth is then

Table 18.6 *Pigments in house paint*

Pigment	*Constituents*	*Comments*
White pigments:		
Chalk	Calcium carbonate	From natural resources; not very strong in oil paint
Glass white	Ground, recycled glass	At an experimental stage
Lead white	Lead carbonate or lead chromate	Highly toxic; also used as siccative
Titanium white	Titanium oxide	Most widely used white pigment
Zinc white	Zinc oxide	Toxic; fungicidal effect; usually produced from recycled zinc
Red pigments:		
Cadmium red	Cadmium selenide	Highly toxic
Chrome red	Lead chromate	Highly toxic
Iron oxide	Ferrous oxide (Fe II)	Originally an earth pigment
Red lead	Lead tetroxide	Highly toxic, anticorrosive
Red ochre	Hydrated ferric oxide (Fe III)	Originally an earth pigment
Brown pigments:		
Burnt sienna	Hydrated ferric oxide, silicic acid	Originally an earth pigment
Umber	Clay containing oxides of iron and manganese	Partly still prepared as an earth pigment, but mostly now prepared synthetically from ferric oxide
Yellow pigments:		
Cadmium yellow	Cadmium sulphide	Highly toxic
Chrome yellow	Lead chromate	Highly toxic
Naples yellow	Lead (II) antimonate	Highly toxic
Yellow ochre	Hydrated ferric oxide (Fe III)	Originally an earth pigment
Zinc yellow	Zinc chromate	Toxic
Green pigments:		
Chrome green	Chromium (III) oxide	Toxic
Green earth	Ferric (Fe III) and ferrous (Fe II) oxides	Originally an earth pigment
Zinc green	Mixture of zinc yellow and prussian blue	Toxic
Blue pigments:		
Cobalt blue	Cobalt (II) aluminate	Occurs naturally as a mineral; slightly toxic; used as siccative
Manganese blue	Barium manganate	Toxic
Ultramarine	Sodium aluminosilicate	Occurs naturally as the mineral lazurite. Prepared synthetically with a mixture of kaolin, soda, sodium sulphate, sulphur, resin, charcoal and quartz
Prussian blue	Iron (III) ferrocyanide	Toxic

Table 18.6 *(Continued)*

Black and grey pigments:		
Bone black	Carbon, calcium phosphate	Prepared by charring different organic materials, animal bones and wood
Carbon black	Carbon	Prepared from amorphous carbon which occurs from burning oil and tar products
Slate grey	Slate flour	Seldom used; obtained through grinding and making a paste of the slate

ground in a mortar, adding water. It is finally dried and the binder is added.

Mineral pigment is obtained by cleaning natural minerals. Synthetic mineral pigments are extracted by combustion (e.g. zinc white), calcination (e.g. ultramarine) or precipitation in a solution (e.g. chrome yellow). Compared with the natural earth colours, the synthetic variations are more homogenous. With the exception of umber, most inorganic pigments today are produced synthetically, which therefore often makes it difficult to restore colours in ancient buildings.

Organic pigments are less durable than the inorganic pigments. One natural organic pigment is coal black, which is made of charcoal preferably from willow, beech or maple. Organic pigments are not normally used nowadays for painting buildings, with the exception of some blues and greens.

Many mineral pigments are based on limited or very limited reserves. The production of pigments normally involves high energy consumption and pollution. This is particularly the case for cadmium, chrome, manganese and lead products; pollution occurs in the factory environment and when the waste is deposited in the surroundings. The production of white pigments also causes a great deal of pollution, particularly in the case of titanium white, where the energy use is also exceptionally high.

Pigments are relatively well bound within paints, and they are less chemically active. However, where paint is applied by spraying, it is spread into the air as small droplets and pigments can be inhaled. Welding of painted objects, scraping, sanding or removing paint with hot air can all cause the same problem. Pigments containing chrome are strongly oxidizing and thereby irritating and damaging to the respiratory system. Zinc chromate can also cause chrome allergy. Chrome, cadmium and lead compounds are, amongst other things, strongly carcinogenic. Ferric oxides can be considered relatively harmless.

In the indoor environment pigments are normally harmless if they are well bound with the paint and not too exposed to wear and tear. Children have, however, been poisoned by licking painted surfaces. Alkylphenol ethoxylates (such as nonylphenol) are often used in pigment pastes as a dispersal agent. These are thought to be harmful environmental estrogens.

Energy recycling of painted products can lead to emissions of toxic pigment vapours. Material painted with products containing heavy metals represent a considerable pollution hazard and must be treated as special waste. The same is true of zinc white, whereas titanium white is not a problem as a waste product (Figure 18.2).

18.2.4 Other additives

Many other additives are used, depending upon the type of paint and where it is to be used.

Anti-corrosion agents are used to prevent rust from being formed in the paint tin itself or when painting metal surfaces such as nails, etc. Traditionally they contain chrome and lead compounds. In water-based paints a mixture of sodium benzoate and sodium nitrite is used in proportions of 10:1, and makes up around 0.5% of the paint.

Anti-skinning agents are added to stop a skin forming on top of the paint in the tin. The substances used are butyraldoxime and methylethylketoxime, added in proportions of 0.1–0.4%.

Dispersing agents are used in dispersion paints to keep the particles spread throughout the suspension. Much used are soylecithin, polyacrylates and alkylphenol etoxylates (such as nonylphenol).

Drying agents (***siccatives***) are added to various oil paints to shorten their drying time, particularly in linseed oil paints. Common siccatives are found in zirconium, cobalt salts and manganese, added in proportions from 0.02 to 0.1% of the dry content in the binder. Lead salts were once used in proportions between 0.5 and 1.0% of the dry content. Alternative siccatives are natural drying oils like cedar oil and oil from the Chinese *tung* tree, which should be added in proportions between 2 and 10%. Addition of pulverized lime will also reduce the drying time.

Drying retardants are added to water-based latex paints. They help reduce the evaporation of water while painting is taking place, and usually consist of glycols and glycol ethers. For a long period after painting is complete, glycols can be emitted and irritate the respiratory system.

Emulsifying agents, mostly as natural proteins, are used in emulsion paints to promote the suspension of for example oil in water.

Fibre materials can be added to paint to make it tougher and provide reinforcement on difficult surfaces. Glass fibre and polyester fibre are often used.

Fillers are simple, colourless materials with the primary function of economizing and spreading the paint, and in some cases of improving the opacity. They also make the paint more matt. Important fillers are kaolin, dolomite, talcum, sand, fossil meal, diabase, baryte and calcite. In the traditional earth colours, neutral clays were used as fillers.

18.2

Indication of a colour scale with pigments having less environmental risk.
Source: Jordfärg EF.

Film-forming agents are much used in water-based synthetic paints in quantities from 1–5%, usually as triethylene glycol n-butylether, polythylene glycol, butyl glycol and 2,2,4-trimethyl-1,3 pentandiol monoisobutyrat (Texanol).

Foam reducers, usually glycerides, are often added to water-based paints so that the paint does not froth.

Fungicides are often necessary to prevent the paint from attack by mould during storage and after application. The least toxic alternatives are lime and metal sulphates such as alum and ferrous sulphate, which are used in many paints with organic or even mineral binders. Some pigments also have preservative capacities. Paints with 50% zinc white are not attacked by mould. Water-based synthetic paints and some paints using organic solvents can contain fungicides based on chlorinated hydrocarbons. Up to the end of the 1970s, the very toxic polychlorinated biphenyls (PCBs) were used. Common fungicides today are isothiazolinones (e.g. Kathon), 2-brom-2-nitro-1,3-propandiol (Bronopol), N-(trichlorometyltio)ftalimid (Folpet), dicloftuanide, tolylfluanide, tetrachloroisophthalodinitrile (Chlorothalonil), methyl 2-benzimidazolecarbamate (Carbendazim), formaldehyde and tributyl tin. Fungicides typically make up 0.5 to 3% of the paint mixture. All fungicides are more or less volatile and can cause problems in the indoor environment. They can irritate the mucous membranes and, in some cases, trigger allergies. Several of the fungicides are also potent environmental toxins, including carcinogens and mutagens.

PH-regulating agents can be added to water-based plastic paints to increase the pH value and thereby reduce the chance of mould growth. Ammonia or triethylamine are often used.

Perfume is added to a few water-based paints, mostly to neutralize the unpleasant smells from chemicals such as amines.

Softeners are used in water-based synthetic paints. Dibutylphthalate (DBP) and dietylhexylphthalate (DEHP) are much used, and even chloroparaffins in certain products. Softeners are released from the painted surface for a long time after it has been applied, and can be both irritating to the mucous membranes and cause allergies. In many modern paints the need for softeners are avoided by using a copolymer binder.

Thickeners are added to water-based plastic paints to give the paint a slow flowing consistency. Water soluble cellulose glue or derivatives of polyurethane and polyacrylate are used for this.

18.3 PAINTS WITH MINERAL BINDERS

Mineral paints are matt and are best suited for painting on mineral surfaces, although they can be used on unplaned timber surfaces. The most common types are based on binders of lime, cement and waterglass, all of which are soluble in water.

The products are based on rich reserves. The environmental consequences of the production techniques can be acceptable. All products are however strongly alkaline and when damp have a corrosive effect on the skin.

Mineral paints are practically emission free in the indoor environment. They are also permeable to vapour transport and do not block the moisture-buffering properties of the materials underneath, and they are not electrostatically charged. Lime and cement paint if not well bound to the surface can flake off and cause respiratory irritation.

As waste the products are inert and will not lessen the painted product's potential for energy recycling.

18.3.1 Lime paint

In lime paint the binder is slaked lime. Curing is based on carbonizing slaked lime with carbonic acid in air, forming an even crystalline layer. The pure lime colours give matt, absorbent surfaces that are difficult to wash. The paint is porous to vapour and not elastic. It binds best to a fresh lime render but can also be used on cements, brick and rough timber, on the latter preferably with casein added to make the paint more elastic. In commercial products additions of styrene can be found.

It is important that lime paint is applied in thin layers. It can be used both inside and out, but walls painted with lime paint cannot be painted over with any other type of paint; the lime paint must be completely removed, which is easily done with a steel brush.

It is important that the pigments are compatible with lime and if more than 5 to 10% is added to pure lime paints, the binding strength of the lime is reduced. The following are considered compatible with lime: titanium white, yellow ochre, red ochre, brown ochre, cadmium yellow, chrome red, chrome green, ultramarine, cobalt blue, green earth, umber, terra de sienna, ferric oxide black, ilmenite black and bone black.

Factory manufactured lime paint has dolomite added to improve its durability, plus a little collagen glue or cellulose paste to improve ease of application and opacity. Water soluble glue is eventually washed out.

Lime paint gets dirty easily in urban environments. It is very sensitive to acids, which break it down to gypsum. It is therefore debatable whether this paint should be used in an area with an acidic atmosphere. The surface underneath is, however, protected from acidic attack, as the lime acts as a sort of sacrificial layer.

RECIPES FOR LIME PAINT

Painting should be carried out during damp periods, and the painted surface protected from direct sunlight for at least 14 days after it is complete. The walls to be painted should be moistened beforehand with lime water – part of all lime paint recipes. Lime water is made as follows:

1. 'Wet' slaked lime is mixed with water in a proportion of 1:5.
2. The mixture is stirred well until all lumps are gone.
3. After 24 hours all the lime has sunk to the bottom. The water above the lime is lime water. The layer of crystals that has formed on the surface must be removed. Lime water is strongly alkaline, with a pH of about 12.5.

Lime milk is also an important ingredient in the paint. It is quite simply a dispersion of solid slaked lime and lime water in the form of lime solution. A very fine grained calcium hydroxide with particles of about 0.002 mm arises through slaking. Lime milk is prepared in the following way:

1. Fresh 'wet' slaked lime is mixed with lime water in a proportion of 1:5.
2. The mixture is stirred well until all the lumps are removed. After about 10 minutes, a good lime milk is created. It can stand several days before use.

Lime surfaces rub off, but this can be retarded by adding a little collagen glue (see page 399), to the lime solution. This method is only for use inside a building.

The pigments best suited for lime paint are ferric oxide colours (yellow, brown, red, black) and ultramarine, which tolerate lime. The pigments should be mixed with water and made into a thick gruel.

Lime paint can best be directly applied onto completely fresh render, and there is seldom the need for a second coat. Old, decayed render, or lime or cement paint, must be brushed clean of dust and dirt if the paint is to bind properly. Lime needs several days to become properly bound to the surface. It is important that the render and the layer of paint do not dry out during this period. In particularly dry weather, the wall should be watered when it feels dry, especially if it is exposed to direct sun.

RECIPE 1: WHITE LIME

The surface is painted with lime water, followed by two or three coats of lime milk, then another coat of lime water.

RECIPE 2A: RED LIME

The earth pigment red ochre is soaked in two parts water overnight to become a pigment paste. The soaked pigment is then mixed with lime water in a proportion of 1:9, to become a lime paint. The wall is first given a coat of lime water, then a coat of lime paint, and is finished off with another coat of lime water.

RECIPE 2B: YELLOW LIME

The earth pigment yellow ochre is soaked in two parts water overnight to become a pigment pasta. The soaked pigment is then mixed with lime water in a proportion of 1:9 to become a lime paint. The wall is first given a coat of lime water, followed by two coats of lime paint and finally another coat of lime water.

RECIPE 2C: LILAC, BROWN OR GREEN LIME

This is made with the pigments ultramarine, umber and burnt umber. The production and application are the same as for yellow lime, above.

RECIPE 3: YELLOW LIME WITH GREEN VITRIOL

This paint has a certain antiseptic effect in addition to the actual effect of the lime. A solution of green vitriol and water in a proportion of 1:5 is made. Then a separate mixture of 'wet' slaked lime and water is made in the proportions 1:5. The two mixtures are then stirred together to become a thick porridge, and water is added. Before painting, the surface is treated with one or two coats of lime water.

RECIPE 4: LIME/CASEIN PAINT

By adding casein to the lime a casein glue is formed which, apart from having better opacity, is also more elastic than ordinary lime paint. This is the type of paint that is used in fresco painting and for wooden surfaces. The paint is waterproof. One part of 'wet' slaked lime is mixed with half to one part of curd (containing about 12% casein), and all the lumps are pressed out. For a purer casein paint, four parts curd are used. To the mixture is added 20–40% stirred pigment of titanium oxide, red or yellow ochre, umber or green earth and thinned out with skimmed milk. The surface is given a coat of lime water before painting.

RECIPE 5: FLOOR TREATMENT WITH LIME

Lime treated floors are light and easy to maintain. First sand the floor and vacuum it. Slaked lime and water are mixed in a proportion of 1:10. The gruel is brushed evenly over the floor with a broom. When dry, the floor is sanded and vacuum cleaned again, then washed with a 5% solution of green soap in lukewarm water. Cleaning of the floor is also done with a 5% green soap solution.

18.3.2 Silicate paints

Silicate paints have their origin in the binder potassium waterglass (see page 90), and were patented in 1938 by A.W. Keim. They can be used on all mineral surfaces but also give good results on rough wood. They can be used as an opaque paint or as lazure paint. Waterglass paints react with lime on a painted surface and form calcium silicate, which acts as a binder. The paint film forms a crystalline layer that has a high resistance against acids. The best results are achieved on fresh render. This paint is more durable than lime paint and has a strong resistance to pollution. Its vapour permeability is about as high as that of lime products.

Some silicate paints have acrylates added to a maximum of 5%, which forms a dispersion product. As long as the surface contains lime, added acrylate will not make the paint stronger. It can also be assumed that the added acrylate shortens the effective lifespan of the paint. For pure waterglass paints, pigment has to be added on site, whilst paint with acrylate additives is ready mixed from the factory.

18.3.3 Cement paints

Cement paints were first used in the 1940s and usually consist of Portland cement and possibly some lime, dolomite or cellulose glue, which is mixed with a small amount of water and then added to the pigment and water. They give their best results on newly cast concrete or fresh render, but can also be used on brick. In durability and quality they fall somewhere between lime and silicate products. Pure cement paint is mainly used nowadays for special treatment of pools and various concrete structures, with large quantities of added polymers.

RECIPE: ORIGINAL CEMENT PAINT

Five parts skimmed milk is mixed with 1 part Portland cement, and pigments that are compatible with lime are added up to a maximum of 5% by weight, to make a gruel. The mixture is suitable for rough wood panelling and masonry. It has to be stirred while being used. The paint is very durable. It was used a great deal by American farmers.

18.4 PAINTS WITH ORGANIC BINDERS

Organic binders consist of synthetic polymers, animal glues, vegetable drying oils and resins, wood tar, cellulose glue and starch.

18.4.1 Synthetic paints and varnish

As with adhesives, synthetic binders can be divided into thermoplastic and thermosetting products. Thermosetting products are often called synthetic resins and are usually based on epoxy, polyurethane or polyesters. Alkyd oil is a polyester product and is the dominant binder in most resin based coatings sold on the consumer market. Important thermoplastic paints are based on polyvinyl-acetate PVAC and acrylates. The binders can be dissolved in water or organic solvents or a combination of these. A wide range of other additives are also needed, often including softeners, dispersion agents, pH-regulating agents, fungicides, drying retardants, film-forming agents, foam reducers and perfumes.

Synthetic paints and varnishes are based on fossil oils. The production is intensive in energy and a wide range of serious pollutants can be emitted. This includes compounds used in the production of polymers as well as different additives. Products containing organic solvents, epoxy and polyurethane are known to create a problematic working environment for painters.

Emissions to the indoor environment can be expected. Organic solvents can be emitted up to six months after application. Many water-based paints also contain other volatile additives which can be released over an even longer period, such as fungicides and softeners. Some synthetic paints and varnishes also emit residual monomers. Most synthetic paints, especially the thermosetting products, have a low vapour permeability, which means that moisture buffering properties in the underlayer will be less accessible. They are also able to induce considerable electrostatic charging, especially when used on floors.

Waste paint should be treated as special waste, even if the pigments are inert. Painted products have little re-use value and normally have a decreased value for material recycling. Flammable materials can be burned for energy recovery in incinerators with high-graded filters.

Epoxy is one of the commercial materials most commonly known to trigger allergies and other problems. At workplaces where people are exposed to epoxy, many of them develop eczema. This is mainly due to the ingredient epichlorohydrin which is also a potent carcinogen. As with another basic ingredient, bisphenol A, it is also a suspected environmental estrogen. Epoxy, even in low concentrations, has a toxic and corrosive effect on water organisms. Ready-cured epoxy products are probably chemically stable, although a certain amount of organic solvent is emitted first.

Polyurethane products contain isocyanates that can easily cause skin allergies and asthma. Sensitization causing permanent damage to the mucous membranes can develop, and asthma attacks can then occur practically independent of the level of exposure. The most exposed places are industrial and building sites, but unreacted residues can also be released within buildings.

Alkyde oil is based on polyester derived from the reaction of an alcohol and an acid anhydride such as phthalic anhydride, modified with vegetable oils to give the mixture drying properties. Paints and varnishes based on alkyde oil came into widespread use during the 1950s and contain large quantities of organic solvents, usually aromates like toluene and xylene. Alkyde oil paint does not penetrate material as well as pure linseed oil paints, but it adheres well to wood even if the surface is not completely dry. Alkyde oil paint is also considered hard wearing, and is used on concrete, plaster and galvanized iron. With no pigment the paint can be used as a varnish.

Alkyde oil is very thick, and because of the high percentage of organic solvent required (between 50–70%), it carries a large risk for the working environment. The emission of solvents in the building can continue for a few days or several months, depending upon the climate of the room, how the paint has been applied and the type of solvent. In certain alkyde oil products, mainly the varnishes, alkylphenols, including nonylphenol, are present in the binder in a proportion of about 1% by weight. Several alkylphenols are seen as environmental estrogens. As corrosion inhibitors in alkyd paint for metal surfaces, additives of lead and zinc are used. These can seep out and pollute the earth, and ground water and should be avoided. A less damaging alternative is aluminium tripolyphosphate.

Thermoplastic products are mostly dissolved as dispersions in water, but small amounts of organic solvents are often added as film-forming agents. They are frequently referred to as latex paints although they do not contain any latex derived from the rubber tree. As binders, polyvinyl-acetate (PVAC), vinyl acetate and acrylates are much used. These move freely about in the water in the form of microscopic plastic pellets. To make the mixture work as a paint, a wide range of additives have to be mixed in. Whilst the binders form about 30% of the product, pigments will make up of 30–35%, fillers 16–20%, water 20–25% and the remaining additives about 5%. Different binders are often mixed to improve the technical properties and reduce the need for additives. Whilst a homopolymer PVAC-paint must have softeners added to make it suitable as a paint, a co-polymer of PVAC and acrylate can do without.

Additives used in PVAC products often include sulphonamides, which can damage the immune system, and alkylphenol ethoxylates such as nonylphenol which are thought to be environmental estrogens. Acrylate monomers can cause eczema through contact with wet paint. Many of the paints can emit volatile compounds for long periods after painting is complete, such as excess monomers of acrylates, styrene, softeners (e.g. phthlates) and fungicides. Several of these can stimulate hypersensitive reactions and lead to allergies. The emissions diminish with time, depending upon the temperature, the moisture situation and the thickness of the paint. After a year most of the emissions cease.

18.4.2 Animal glue paint

Animal proteins consist of both fat soluble (hydrophobic) and water soluble (hydrophilic) compounds, and are therefore well-suited for use in emulsion paints dissolved in water. The products are not especially strong, but usually highly permeable to vapour and are thus suitable for interior use on ceilings and walls. There are mainly two types: collagen glue paint and casein paint. Collagen glue paint is based on waste from abattoirs; casein paint is based on milk.

In buildings, under dry conditions the products are inert and do not lead to electrostatic charging. In combination with damp cement, protein glue paint can emit ammonia that can irritate the respiratory system. Long-term dampness can easily lead to attacks by fungus and other bacteria. The bacteria break down the protein, and the rotting products emit a bad smell and cause irritation.

Waste from this type of paint can cause the growth of algae in streams and rivers. Animal glue paint and casein paint can normally be washed off painted materials, so the materials can be easily prepared for re-use. Painted materials can normally be composted or burned in conventional incinerators.

Collagen glue paint is good for using on dry interiors on masonry, wood, hessian and paper. The surface has to be cleaned of any fats before painting; otherwise a small measure of sal-ammoniac can be added. Its opacity is good, and many pigments can be used. Though the paint is not water proof, experience shows that washing down an animal glue painted wall and applying a new coat is no more work than meticulously cleaning a wall painted with a stronger paint. Animal glue paints can also be used in emulsions, usually with linseed oil. This produces a water-repelling paint.

RECIPE FOR COLLAGEN GLUE PAINT

The paint should not be used in bathrooms or similar areas, or on surfaces exposed to a great deal of wear and tear.

When painting on plaster it is usual to wash the surface with a thin solution of green soap, consisting of 1 part green soap to 50 parts water. This should sink in and dry in order to give the glue paint a chance to penetrate evenly into the plaster.

Painting should be done wet-on-wet so as not to be blotchy. Before being added, the pigment should be mixed with a little water to the consistency of a thick colour paste with no lumps.

RECIPE: GLUE PAINT BASED ON BONE GLUE OR HIDE GLUE (10 LITRES)

The ingredients are 200 g dry bone or hide glue, 5 litres of water, 10 kg powdered chalk and pigment. The paint is prepared in the following way:

1. The chalk is first soaked and left in a bucket overnight without stirring.
2. The powdered glue is treated likewise and left overnight, with water just covering the glue. It is then carefully warmed in a water bath until dissolved.
3. The glue is poured into the chalk and stirred well.
4. The pigment paste should be mixed in. Certain fatty pigments are not easy to dissolve, but this can be improved by adding a teaspoon of alcohol, which breaks down the surface tension. The stronger the colour required, the more chalk must be replaced by pigment.

Casein paint is produced as an emulsion, the milk protein acting as binder. Pure casein products are not water repellent and should be limited to indoor use. When reacted with lime, either when mixed or when painting on surfaces containing lime, a more water resistant paint is achieved, see ‘Lime/casein paint’ (page 394). This is also the case with emulsions of casein paint and linseed oil, see ‘Linseed oil/casein paint’ (page 402).

18.4.3 Vegetable oils

A drying oil dries in the air, while at the same time keeping its elasticity. The most common drying oil is linseed. Hemp oil also provides good quality. To some extent soya oil, olive oil and fish oil can also be used, but these are not actually drying oils.

Linseed oil dries by oxidizing in air and is transformed to a strong and solid linoxine. This oil has been used in paints since the beginning of the seventeenth century and can be used on wood, earth, concrete, plaster and to a certain extent, steel. Linseed oil is also used on stone façades to close the pores and protect it from aggressive air pollution. Plaster and concrete should not be painted during the first year, since moisture emerging from inside the underlay can push the paint off. Oil paint can be produced in matt, half-lustre and full lustre form. The half-lustre and lustre types are very strong and easy to clean. Linseed oil products are generally water resistant with moderate vapour permeability.

Cold pressed oil is seen as being of higher quality than hot pressed oil. Cold pressing, however, only frees about 30% of the oil in the seeds. In hot pressing the seeds are finely ground and pressed while warm, which substantially increases the yield. The oil can also be used as it is, or boiled. Raw linseed oil is probably more robust, especially when cold pressed, but it dries very slowly because of the large amount of protein substances it contains. It is therefore mostly used out of doors. Boiling linseed oil to 150 °C removes the majority of the protein, making the product dry more quickly. The paint can be used both indoors and outdoors.

Stand oil is linseed oil that is boiled without air to 280 °C and thereby polymerized. It is considered to be firmer and more elastic. It also dries quicker than the other types. Even so, drying time is a problem with linseed oil products. In factory produced oils, drying agents (siccatives) are therefore added to a proportion of about 0.5%. This also applies to products for outside use, even if the drying time there is not too critical. For indoor use, it is normal to add drying agents to all qualities of linseed oil, but drying oils such as *tung* oil and cedar oil can achieve the same purpose. Another way to reduce the drying time is to use linseed oil in a water-soluble emulsion with casein glue, collagen glue, starch or egg.

Linseed oil paint often has fungicides added but this is not necessary for interior painting. Emulsion paints are dissolved in water whilst organic solvents are often added to pure linseed oil products to increase penetration and spreading rate. This is usually unnecessary for easy-flowing oils such as cold pressed linseed oil. The amount of solvent varies from about 10 to 30%, and is much lower than the equivalent in alkyde paints. A process for treating floors using highly refined linseed oil has also been developed that does not require drying agents or organic solvents. Application is then performed with a polishing machine.

The raw materials for drying oils are renewable and environmental problems relating to their production are minimal. Products containing a high percentage of organic solvents are an exception to this, and present a risk, especially for painters.

Within buildings, linseed oil products can be regarded as less problematic. During the curing period there will be an emission of oxidation products, mainly aldehydes, which can temporarily irritate the respiratory system but without any known long-term effects (Knudsen *et al*., 2004). Fresh paints and oils containing organic solvents can emit irritating substances. Pure linseed oil products have moderate vapour permeability. Their porosity increases with time, but will still be too small for the moisture buffering capacity of the underlayer to be fully used. An exception is a product where linseed oil is in an emulsion with an animal glue, which is considerably more vapour permeable. Products based on vegetable oils do not cause electrostatic charging.

Materials treated with vegetable oil products are difficult to clean, which will reduce the re-use value. Products with no hazardous substances added can be composted or burned in ordinary incinerators.

RECIPES FOR LINSEED OIL PAINTS AND TREATMENTS

Linseed oil products can be used both inside and outside. For interior use on walls and ceilings, linseed oil emulsions are a better choice because of the short drying time and avoidance of organic solvents. Linseed oil paints are particularly good for interior mouldings and external walls made of timber panelling. This paint type swells in damp weather, creating an elastic film that never completely hardens. When linseed oil has set, it is quite porous to water vapour and allows moisture to evaporate. The choice of pigment is important if the paint is going to retain these properties. Zinc white should not be used as an outdoor pigment. It is easily washed out by acid, rain and dew and, when exposed to ultraviolet radiation, the paint starts cracking, especially on a south-facing surface.

RECIPE 1: LINSEED OIL PAINT FOR OUTDOOR USE

To start mixing linseed oil paints, a colour paste is prepared. The pigment must be thoroughly mixed to an even consistency with a small amount of linseed oil added. The amount of pigment to oil depends upon how transparent and shiny the paint is to be; more pigment will give a more matt paint.

The first coat usually contains about 15% vegetable turpentine to help the oil penetrate the substrate. The final coat does not need solvents, especially if cold pressed oil is used. Adding solvents to the paint generally shortens its lifespan.

RECIPE 2: LINSEED OIL TREATMENT OF TIMBER FLOORS

The floor should be sanded. The first coat usually consists of a mixture of mineral spirits or turpentine with boiled linseed oil or stand oil in the proportions 1:1 and in the final coat in the proportions 1:2. After application, all excess oil should be dried off after 20 to 30 minutes.

RECIPES FOR LINSEED OIL EMULSION PAINTS

Emulsion paints are excellent for interior walls and ceilings. They employ water as solvent, are without fungicides and siccatives and possess high vapour permeability. They usually produce a matt surface and are best used on wood and wood sheeting. When painting plaster and concrete, flaking can occur. Painting wet-on-wet avoids stains. The paints should be applied directly after preparation.

RECIPE 1: COLLAGEN GLUE/LINSEED OIL

The paint is fairly strong, and can be used inside and out, but is best used indoors: 10 parts of collagen glue is mixed as described in the recipe on page 378. Then 2.5 parts of boiled linseed oil is stirred in and the paint is ready for use.

RECIPE 2: FLOUR PASTE-LINSEED OIL/CASEIN PAINT

For interior and exterior wood and masonry: 10 parts flour are mixed with 10 parts cold water, then 50 parts boiling water, to form the glue. Linseed oil in 10–12 parts and 10 parts skimmed milk are added with colour pigment to a proportion of 15–40%.

RECIPE 3: CASEIN/LINSEED OIL PAINT (CASEIN OIL TEMPERA)

For interior and exterior wood: 10 parts sour milk is mixed with 4 parts linseed oil and about 4 parts pigment. The paint has been said to last from five to 10 years externally.

RECIPE 4: EGG/LINSEED OIL PAINT (EGG OIL TEMPERA)

For internal use on wood, egg/linseed oil paint gives a hard, shiny and easily cleanable surface: 1 part linseed oil is mixed with 1 part fresh egg and 1 part water. Pigments are added to a proportion of 15–40%.

PAINT WITH FISH OIL BINDER

Fish oil has been used a great deal in coastal regions up to the beginning of the twentieth century.

RECIPE: NORMAL PAINT WITH FISH OIL

Fish liver is laid in a barrel and put in the sun with a sack over the top. The liver melts quickly to liver oil, is mixed with red ochre, yellow ochre or similar pigments and can be dissolved in alcohol if necessary. The paint is very durable and has good resistance to salt water.

18.4.4 Tar

Wood tar gives a weak brown colour, due to coal dust and pitch. Pigments such as red or yellow ochre can be stirred in. To improve applicability, the tar is most often supplemented with linseed oil or alkyde oil and thinned with organic solvents; fungicides can also be added.

Wood tar is extracted from both coniferous and deciduous trees and is usually rich in polycyclic aromatic hydrocarbons (PAHs). An exception is tar extracted from beech. PAH substances such as benzo(a)pyrene are carcinogenic and mutagenic. Tar products should not be used indoors. When used outdoors, the PAH substances will filter into the soil.

Re-use and recycling of painted products can be a problem. As waste, the product should be deposited at special dumps.

18.4.5 Natural resins

Several different types of natural resins can be used for varnishing wood. To make the resin more fluid, organic solvents are most often added.

Colophony is extracted from the resin of pine trees after distilling vegetable turpentine oil, and consists mainly of abietic acid. It can be dissolved in alcohol or turpentine. Copal, a fossil form of resin, is extracted in India, the Philippines, Australia and Africa; alcohol or turpentine is used as a solvent. Shellac comes from the Bengal fig tree (*Ficus bengalensis*) when it is attacked by wood lice; alcohol is used as a solvent. Dammar comes from special trees in East India and Malaysia (*Dipterocarpaceae*); alcohol or turpentine can be used as solvents. Sanderac is drawn from the juniper gum tree (*Callitris quadrivalis*) in Morocco; it dissolves in alcohol, turpentine, ether and acetone. Rubber mastic is extracted from the resin of the mastic tree (*Pistacia lentiscus*) found on Mediterranean islands; it dissolves in alcohol or ether. Elimi gum is resin extracted from amyris trees (*Burseraceae*) on the Philippines, Mauritius, Mexico and Brazil; it dissolves in alcohol, petroleum or turpentine. Acaroid resin is from the grass tree (*Xanthorrhoea australe*) in Australia; it dissolves in alcohol.

These products are mainly based on renewable resources, with the exception of some types of solvents. During application, substances can be emitted by the solvent vapour that can lead to respiratory ailments and allergies. Also some of the resins themselves can emit irritants. Colophony is a well-known allergen. These emissions can continue after the building is finished. A varnish layer of natural resin is about as vapour-proof as a synthetic products and the moisture regulating properties of the underlayer is thus aborted. As waste, these products are normally not a problem, depending partly upon the pigment used.

18.4.6 Starch paint

Starch paint is based on starch glue made from rye or wheat (pages 379–380) and is mainly used externally on planed timber. The paste decays over time and only pigment is left. This can rub off. To compensate, it is common to add about 5–7% linseed oil in an emulsion. For use in damp environments 1–2% green vitriol can be added to prevent mould attack.

Starch paint has high vapour permeability. It does not flake or peel and is easy to apply and maintain. It is resistant to fungal attack. Tests have shown it to have better durability than other commercial paints (Hansson, 1999). In Scandinavia, starch paint has a long tradition of being commonly tinted with red or yellow ochre pigments.

Starch paint is based on renewable raw materials from plants and represents no environmental threat, either in its production or use. Reuse and recycling of treated materials is acceptable, as is burning for energy recovery. The materials can normally be composted. However, the favourable environmental profile can be reduced by the addition of environmentally damaging pigments.

18.4.7 Cellulose products

There are two different cellulose paints; one based on cellulose paste, the other on nitrocellulose. The latter is used mainly for varnish and must contain up to 75% organic solvents and softeners. The cellulose paste paint has approximately the same properties as collagen glue paint.

Cellulose paints are mainly based on renewable resources from plants. The products are made from methyl cellulose in a highly polluting process. The production and use of organic solvents in products of nitrocellulose are damaging both to nature and to the painter.

Within buildings these products are not a problem. Painted material can probably be burned in normal incinerators or dumped on domestic tips without any problem, with the possible exception of varnishes of nitrocellulose when hazardous substances have been added.

18.5 STAINS

Stains are used on wood and do not contain added binders. There are two main types of stain: *chemical stain* and *water stain*.

Chemical stain is based on a colour reaction with substances in the timber. Tannic acid can be used, as can green vitriol. Lye treatment is based on sodium hydroxide (NaOH) often with lime or titanium white added (Figure 18.3). In commercial products small additions of vegetable oil, from soybeans or coconut, can be found. Interior surfaces exposed to heavy wear should have an extra treatment of green soap or vegetable oil to facilitate cleaning.

Water stain is made with pigments that are soluble in water. Modern exterior stains usually also contain metal salts such as cobalt chloride,

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Wooden surfaces treated with lime lye. Gaia Lista, 2008.

copper chloride, potassium dichromate, manganese chloride and nickel chloride, in order to impregnate the wood. Several ordinary pigments can be used in the stain; but even bark or onion peelings are used as stain colours.

Stains are fully open to vapour and therefore the full potential for moisture buffering in the underlayer can be utilized. Stains are also the least resource demanding treatments and they are relatively problem free in both production and use. Exceptions are water stains with metal salts added. These are usually toxic and can seep into the soil. The same can be said for the waste from these stains and they require special waste treatment. As far as the other products are concerned, re-use, recycling, composting and dumping are all relatively problem free. It is only the addition of poisonous pigments that reduce the quality of an otherwise very positive environmental profile.

RECIPES FOR CHEMICAL STAINS

RECIPE 1: NORMAL STAIN

An amount of 10 g tannic acid is dissolved in 1 litre warm water. The stain is applied cold. It is usual practice to then apply a second layer consisting of a solution of 10 g potash (K_2CO_3) in a litre of water. The colour is light grey–green.

RECIPE 2: LYE STAIN

An amount of 5 g of tannic acid is dissolved in 1 dl lukewarm water; 50 g potash is dissolved in 5 dl hot, almost boiling water, and 4 dl cold water and 1.25 dl lye solution (12% lye in water) are added. The tannic acid solution is mixed with the potash solution. This must be prepared in a ceramic vessel. It gives a stronger grey–green tone than the first recipe. The final colour emerges after eight to 14 days. The stain should stand a few days before use. Lye stains are highly alkaline, and protective clothing must be used.

RECIPE 3: IRON VITRIOL (GREEN VITRIOL)

Iron vitriol is based on ferrous sulphate (iron(II)sulphate). In liquid form it can irritate skin. A good impregnation solution consists of 10–13 g per litre of water, with a little alum added as a fix, and gives the timber an even and shiny silver surface. Green vitriol also has a slight impregnating effect as well as being a flame retardant.

RECIPES FOR WATER-BASED STAINS

RECIPE 1: ONION PEEL STAIN

The onion peel is boiled in water for 15 minutes to a weak pink colour. The solution is applied to wood, giving a faint yellow colour.

RECIPE 2: BARK STAIN

The bark to be used has to be gathered during the summer. The colour is extracted by pouring a 5% soda solution over the bark and letting it stand for four weeks. For 250–500 g bark, 250 g soda and 5 litres boiled water are used. After four weeks the mixture has a very strong smell, but after an hour's simmering the smell disappears.

A brown colour is achieved by using beech, apple and spruce bark and a yellow colour from poplar and cherry bark. The latter needs a 10% soda solution.

The bark of ash gives a grey–green colour, and birch gives an apricot colour using a 10% soda solution.

18.6 BEESWAX

Beeswax is particularly suitable for the treatment of floors and bathroom walls. It fills cracks and pores in timber and prevents vermin from laying eggs. Wax is usually dissolved in mineral spirits or turpentine and can also be thinned out with linseed oil. It can be coloured with earth or mineral pigments. The wax is easy to clean, but does not have much resistance to water, so more hard-wearing surfaces should be saturated with oil first.

Beeswax is a renewable resource that creates no problems in its production or use. Organic solvents will be a health risk during application, and can even cause problems in the indoor environment for a short period after application. Re-use of treated materials, recycling, energy recycling and composting or dumping create no problems.

RECIPE FOR WAX TREATMENT: BEESWAX ON WOOD

Three parts wax (first melted in a water bath of 70–80 °C) is mixed with one part turpentine. The mixture can be applied directly onto wooden walls. Floors have to be well-sanded first, and the surface temperature should not be below 20 °C. When the surface is dry (this should take a couple of days), it is ready to be polished. It must be waxed once a month where it is most worn. It can be cleaned with a damp cloth and warm soap water.

18.7 GREEN SOAP

Green soap is used for the treatment and saturation of wood, usually floors. It consists mainly of fats from linseed oil or timber oil which are boiled out and saponified with lye. Fats from maize, cotton seed and soya oil can also be used. Small amounts of waterglass and soda can be added; soda increases its washing ability somewhat, but at the same time decreases the effective amount of fats. Green soap is relatively alkaline and hinders the growth of bacteria and mould.

Green soap is based mainly on renewable resources from plants and is free of problems both in production and use. The same is true for the re-use of treated materials, recycling, energy recycling and composting or dumping.

RECIPE FOR GREEN SOAP TREATMENT

The floor must be dry and preferably newly sanded. A mixture of 1–2 dl solid green soap per litre of hot water is poured over the floor. It is worked into the timber in the direction of the floorboards. The floating soap water is soaked up without completely drying the surface. The surface is allowed to stand overnight, and the treatment is repeated four or five times. Before the final treatment, the raised fibres can be sanded with a paper of grade 120–150 in the direction of the boards. A stronger treatment can be achieved by adding lime (see page 395, Recipe 5).

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19 Impregnating agents, and how to avoid them

As has been illustrated in several chapters in this book, wood is, for most purposes, a good choice from the environmental point of view. However, where possible, wood should be used in a way that ensures a long lifetime and, as far as possible, not be treated with toxins or additives.

Wood and other organic materials are easily attacked by insects and fungi in damp conditions. In central and Northern Europe, six types of insects are especially attracted to timber buildings (see Table 19.1)Table 19.2. Fungus is a type of lower plant species that lacks chlorophyll. Fungi that attack buildings can be divided into two main groups, *discolouring fungi* and *disintegrating fungi*. Discolouring fungi give timber a superficial discoloration, without decreasing its strength. Disintegrating fungi attack the cell walls in timber and destroy the wood.

Spores from disintegrating fungi are ubiquitous. They spread with the wind in the same way as pollen, and attach to anything. These fungi belong to nature's renovating corps, their main operation being the breakdown of dead organic material, which regrettably includes many building materials. The optimum conditions for this phenomenon relate to dampness, temperature and acidity. Dampness in organic material needs to be from 18 to 25%. Humidity above or below these figures is not attractive to these spores. The majority of fungi, however, survive long dry periods. A temperature between 20 and 35 °C makes an attack possible, but there is no activity below 5 °C. Disintegrating fungi do not strike in environments with a high alkaline content, i.e. with a pH over 6.0. One exception is the *Merulius lacrymans*.

There are four principal ways to avoid attack from insects and fungi:

1. Use of high quality material in exposed locations.
2. Structural protection of exposed materials.
3. Use of non-toxic treatments: passive impregnation.
4. Use of toxic substances: active impregnation.

The toxic preservatives are usually divided into *insecticides* and *fungicides*. The concept behind them is the creation of biological toxins that kill, which frequently has unforeseen consequences for other animal species, not least humans. The main task of this chapter is to show how these substances can be avoided.

Table 19.1 *Vermin*

Type	*Comments*
House longhorn beetle (Hylotrupes bajulus)	Does not attack heartwood in pine
Carpenter ants (Camponotus herculeanus)	Does not live on wood, but uses it as its home and lays eggs, even in pressure-impregnated wood
Common furniture beetle (Anobium punctatum)	Prefers a temperature of 20–25 °C and a relative humidity of 50%, only found in coastal areas
Woodworm (Dendrobium pertinax)	Attracted to wood that has already been attacked by fungus
Violet tanned bark beetle (Callidium violaceum)	Dependent on bark left-overs for its survival
Bark borer (Ernobius mollis)	Dependent on bark for its survival

19.1 CHOOSING HIGH QUALITY MATERIAL

In old trees of most species, a large part of the trunk consists of heartwood, which has a strong resistance to fungi and insects. Not even the house longhorn beetle can penetrate the heartwood of pine. Heartwood was traditionally used in log construction and external panelling and, until the nineteenth century, in windows and doors.

Initially, pine was thought to be more durable than spruce, but this conclusion has been modified. The core of pine has almost no moisture absorption capacity, whereas the sapwood has a moisture absorption capability (lengthwise in the cells) 10 times greater than that of spruce. Pine cladding from the young core is therefore less protected than spruce. Birch cladding is even weaker; its permeability is about 1000 times greater than that of spruce. Generally speaking, the absorption of moisture increases in relation to the breadth of the growth rings.

Table 19.2 *Minimum slope of roof to prevent water seeping in*

Type of roof covering	*Normal situation (°)*	*Exposed location (°)*
Corrugated metal sheeting	10	14
Concrete roof tile	15	22
Corrugated cementitious sheeting	14	18
Slate, single layer	22	30
Slate, double layer	20	25
Fired clay tile, interlocking	20	30
Bituminous shingle	18	22
Bituminous roofing felt, two layers, welded	3	3
Plastic membranes, welded	2	2
Timber, shingle and plank roof	22	27

The manner of sawing plays an important role. There is least warping and cracking in planks with standing annual rings (see Figure 10.4). This greatly reduces the likelihood of water penetration and fungal attack.

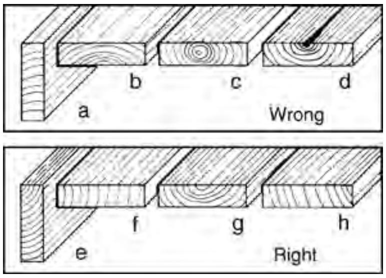
Timber should be felled in winter, because wood felled in summer has a much higher sugar content, making it more attractive to insects and micro-organisms. By removing the bark from the felled trees, attacks by bark-eating bugs are avoided. Sawn timber should be dried to 20% moisture content before spring, and logs that are not going to be sawn should be stored in water. In northern climates, pine for log construction should be felled in September and profiled on both sides during the spring. It should be dried during the summer and used as building material in the autumn. See more about preventative sawing and drying routines on page 169–170.

Material from a building that has recently been attacked by the house longhorn beetle or the common furniture beetle should not be re-used.

19.2 STRUCTURAL PROTECTION OF EXPOSED COMPONENTS

If buildings have been constructed with materials so that air circulates easily, and keeps them dry, then fungus will not attack.

All types of timber should be used in a way that allows movement to take place; otherwise splitting and gathering of moisture will occur. The heartwood side, which is generally the least moisture absorbent, should be on the outside (Figure 19.1). Moisture is usually most quickly absorbed at the ends of the timber. The end grain must therefore be protected. Exposed ends of beams can be cut at an angle or preferably covered.

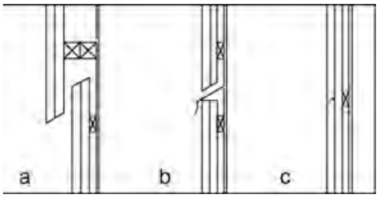


19.1

Protective principles for outdoor use of timber (balconies etc.); a-b: Exposed tangential sides; c-d: Exposed radial sides, but the pith and the juvenile wood will make the wood shake and deform; e-h: Exposed radial sides without pith.
Source: Träinformation, Sweden.

Panelling should be well ventilated. The more exposed a wall is to driving rain, the wider the air gap behind the panelling should be; this is usually 5 cm in very exposed areas, and about half that in normal inland situations. Horizontal battens fixed directly to panelling should have a sloping top side, or be mounted on a vertical batten system against the wall. The distance of the panelling from the ground should be at least 20–30 cm.

The bottom end of vertical panelling should be sawn at an angle so that drops are formed and let off on the outside face of the timber (Figure 19.2). The root end should be pointing downwards as it contains more heartwood. Water may collect in the joint between the two layers of vertical panelling. Along the coast where there is plenty of driving rain, this often results in rot, as drying periods can be very short-lived. On the coast, panelling should therefore be horizontal. This also gives the advantage of less exposed end grain. Rot usually occurs at the bottom of the wall, and with horizontal panelling it is quite easy to remove and replace a few planks; with vertical boarding all the planks would be affected.



19.2

Protective splicing of vertical panelling. Type (a) and (b) are highly protected while type (c) will easily shake and crack, especially around the nails. Source: Trätek, Sweden.

In particularly damp areas, the colour given to the surface can also play a part. A dark ochre colour can reach a temperature of up to 40 °C higher than a white surface in sunny weather. This can be a significant factor for drying times. In damp places where, even during the summer, there are only short periods of sun between showers, the drying time needs to be as short as possible. However, if the temperatures get too high, splitting or cracking can occur, which can also increase the intake of moisture.

Combinations of wood with metal, lime and cement-based mortars and concrete can cause problems. Condensation can occur around metal components, while in combinations with cement and lime, alkaline reactions can arise which increase porosity and moisture absorption in the timber.

19.3 METHODS OF PASSIVE IMPREGNATION

Methods of passive impregnation are partly aimed at enhancing a timber's natural capacity to withstand insects and fungi, as well as partly reducing access to nutrients and humidity.

Self-impregnation is a well-known traditional method used in most cultures. The usual procedure is to lop off the top of a pine or similar tree and remove a few stripes of bark from the bottom to the top. Three or four of the highest branches are left to 'lift' the resin. After a few years, the whole trunk is filled with resin and the timber will gain a quality similar to heartwood.

Cleaning out the cell content makes the timber less attractive to most insects and fungus. This can be achieved by storing it under water for a time. In salt water the results will be even better due to the salt absorbed, since this has an antiseptic effect.

In the past, it was common practice in Scandinavia to boil wooden shakes before they were used for roofing. Boiling is a very effective way of washing out the content of the cells.

Heat treatment. Burning the outer layer of wood is a traditional way of increasing the durability of any part of the wooden piles that were going to be placed underground. The carbon coating that forms lacks nutrients and is almost impenetrable to insects and fungus. The heating also enriches phenolic resins and aldehydes in the outermost part of the pile. These are natural biocides. The greatest impact occurs with pine, which is rich in resin, while burning spruce and deciduous trees is not so effective. During burning the timber can easily split, and it is easy for fungus to get access through the splits, so burning must be carefully controlled, preferably by using a blow lamp. The depth of the burning should be 1–3 mm, after which the surface is brushed with a bronze brush. This process takes a long time. Julius Caesar described the technique in his book *De Bello Gallico* in connection with setting up fortifications in the Roman Empire. This method has also been used for centuries in Portuguese and British timber warships, as it not only increases resistance to rot but also makes the surface less water-absorbing.

A modern version of heat treatment is done by heating the timber, usually pine or spruce, in a closed chamber at 200 to 250 °C for

24 hours. The process is quite energy intensive, but in addition to increasing the timber’s resistance to fungi, it gives the wood a golden brown patina which has made it an attractive competitor to tropical hardwoods. This method seems to give the timber the same resistance as heartwood (Edlund, 2004).

Chemical modification is a process that normally uses acetylation through a process whereby the timber reacts with acetic anhydride – which comes from acetic acid (see page 177). This effectively reduces the ability of wood to absorb water. The result is a highly stable timber that is no longer digestible. The resultant resistance against fungi is greater than for heat treated timber and about the same as for timber impregnated with copper (Edlund, 2004).

In a second type of chemical modification, furfuryl alcohols produced from biomass waste such as sugar canes, corn cobs and sunflower are used. The furfury alcohols are driven by pressure into the cell walls of the wood and heated with steam (80–140 °C) for 6 to 8 hours to achieve polymerization. The impact strength of the wood is thereby strongly reduced, but at the same time a higher stiffness is achieved, and the treated wood is no longer attractive to fungi (Figure 19.3).

In a third type of chemical modification, the cells in the wood are filled up to 90% with synthetic monomers. After heating and gamma radiation a plastic polymer is formed that is virtually inaccessible for fungus and insects.

Seen from the environmental point of view there is no doubt that acetylation and furfurylation are preferable to this last method. As with normal timber these treatments involve few environmental doubts. The chemicals are based on renewable resources and the timber will be suitable for energy recovery. If modified with synthetic polymers the waste will have to be treated like other plastics.

Saturation with linseed oil is done by pressure treating the timber with linseed oil, in amounts of about 90 litres per m^3 of timber. The cell pores are then filled and thus become inaccessible to insects and fungus, as in heartwood. Linseed oil treatment is also water repelling. The resistance against fungal attack is considered equal to treatment with copper based fungicides (Edlund, 2004).

pH-regulating substances can be used both as a preventive measure against fungal attack and for remedial treatment. Mould will not grow if the pH level is higher than 6.0. Treatment with pH-regulating substances is also effective against insect attacks. Exceptions are the fungus *Merulius lacrymans* and the longhorn house beetle, which are not affected. The pH-regulating substances available are primarily alkalis such as clay, cement, lime, waterglass and lye. Treatment with lye also brings the resins and tar to the surface of the wood in the same way as burning. The pH-regulating substances are not poisonous in themselves, so they do not cause problems in the indoor climate of the building or for the surrounding environment.

19.3

Exterior woodwork modified with chemicals from biomass waste. Source: Kebony products.

TREATMENT WITH WATERGLASS

Waterglass (see page 90) is very alkaline. In addition, it forms a coat so hard that insects cannot penetrate it to lay their eggs. It is, however, susceptible to leaching when exposed to rain, and can therefore only be used indoors or on protected parts of the building. Waterglass needs a rough surface; it does not bind well to a planed surface. It is dissolved in boiling water and applied to the wood with a brush. It can also be applied to straw materials, using a solution of one part waterglass to two parts water. Waterglass is often used as a flame retardant and it is very open to water vapour.

LYE MADE FROM SODA AND POTASH

The soda solution is made by boiling 1 litre of water with 50 g of soda powder. The liquid is applied when still warm. Potash solution is either based on pure potassium carbonate or on wood ashes, which contain about 96% potassium carbonate. A potash solution is made up by boiling 1 litre of water with 0.5 litres of pine ash and letting it simmer for 15 minutes. The solution is sieved and applied while still warm. The treatment has to be repeated every two to three years.

Soda and potash lye have been used for surface treatment in many Swiss villages for hundreds of years, and the buildings have kept well. A drier climate is, of course, partly responsible for their success.

19.4 METHODS OF ACTIVE IMPREGNATION

Experience has shown that timber with a high content of tar and resin lasts longer than timber with a low content of either. This is partly because the timber is harder and partly because these substances have ingredients that are poisonous to fungus and certain insects. Traditional types of timber protection aim to increase the quantity of such materials by covering the timber with tar. Extract from bark has also been used to impregnate oak, birch and spruce, with good results. This method was once so popular that bark extract became a major Norwegian export. Over 2000 years ago the Chinese used salt water as an impregnating agent. Wood containing more than 5% of table salt (sodium chloride) is not susceptible to fungus. The modern version of this is the use of metal salts. Wood tar has mostly been replaced by derivatives of fossil oil (Table 19.3).

Since forestry was industrialized, the general quality of timber has deteriorated considerably, and the need for biocides has rocketed over the last decades. New fashions in architecture, which include highly exposed exterior timber structures, have accelerated this trend.

For active impregnation the following functional qualities are desirable:

- Enough poison to prevent attack from fungus and insects.
- Not be poisonous to people or animals.
- The ability to penetrate into the material.
- Resistant to being washed out or vaporized from the material.
- Free from damaging technical side effects such as miscolouring, corrosion of nails, etc.

Unfortunately, an impregnating substance with all these qualities does not exist. There is generally a clear relationship between toxicity and effectiveness. Effective poisons such as metal salts have particularly damaging effects on the environment, including humans. Less damaging substances such as bark extract and ferrous sulphate are at the same time less effective and susceptible to rapid leaching.

Preventive impregnating agents must be differentiated from treatments that are used after the material has been attacked. The same substance can, however, often be used in both cases. To make the mixtures fully effective, both fungicide and insecticide may be needed in the same mix. They are dissolved in water or organic solvents.

Table 19.3 *Active substances in fungicides and insecticides*

Type	*Fungicide*	*Insecticide*	*Toxicity*
Mineral based			
Arsenic salts	x	x	Very high
Aluminium sulphate	x		Low
Boric acid, oxides and salts	x	x	Medium
Copper and copper salts	x		Medium
Ferrous sulphate	x		Low
Fluorine salts	x		Medium
Sodium chloride (table salt)	x		Low
Zinc and zinc salts	x	x	Medium
Oil and coal based			
Creosote	x		Very high
Endosulphane		x	Very high
Hexachlorobenzene (Lindane)	x		Very high
Parathion		x	Very high
Pentachlorophenol		x	Very high
2-Phenylphenol (Preventol)	x		Medium
Pyrethrin (Permethrin)		x	High
Triazole (Propiconazole)	x		Medium
Tributyl tin	x		Very high
Wood based			
Bark extract	x		Low
Tar from softwood	x		High
Tar from beech	x		Low
Wood vinegar	(x)	(x)	Low

The substances are applied to the timber by pressure/vacuum treatment or by dipping/brushing on.

Apart from creosote (composed of polycyclic aromatic hydrocarbons), pyrethrine (Permethrine) is the most common oil derivative and has superseded such derivatives as pentachlorophenol, which were phased out during the 1980s and 1990s because of high environmental and health risks. The most important metals used for impregnation are arsenic, chrome and copper where copper is regarded as least toxic.

There are different classes of impregnating substances; when in contact with the ground, timber requires strong substances in large doses, but in well-ventilated, outdoor cladding, a much weaker mix will be effective enough. A strong salt impregnation agent usually contains a mixture of copper, chrome and arsenic salts (CCA) where arsenic and copper are the biocides and chrome acts as fixative, however still highly toxic. For timber above ground level it is quite adequate just to use copper compounds.

Both metal and fossil oil products are based on very restricted resources.

Production of impregnating substances and the work at manufacturing workshops can result in emissions of strong biological toxins to earth, air and water. Heavy metals are highly toxic and have large biological amplification capacities. Also frequently used fluorine salts, zinc salts and borates have serious toxic effects. From the impregnation industry based on fossil oils, vaporized solvents can be released as well as a range of chlorinated hydrocarbons. Many of these will, in the same way as heavy metals, have a capacity for biological amplification.

In the house, solvent-based tributyltin, zinc and copper-naphthenates volatize, potentially exposing the occupants to their toxic fumes. Water-soluble metal salts are usually stable in buildings. They are, however, released from exterior surfaces exposed to rain and may contaminate ground water and soil. Normally about 30% of the metal salts will leach out in the course of a 30-year period (Hansen, 1997). Acid rain increases the rate of leaching. These substances will quite easily combine with earth particles which delays the drainage and spread of the substances to some extent. Pure sand will not have this effect. Leaching will also occur with the oil-based products. These also have gaseous emissions to air. In creosote impregnated buildings, considerable concentrations of naphthalene have been registered inside buildings even when the application has been outdoors (Gustafsson, 1990). Creosote combined with solar radiation can also cause rapid and serious burning of the skin.

If creosote-impregnated timber is combusted at temperatures under 350 °C, the entire contents of polycyclic aromatic hydrocarbons (PAH) will be emitted with the chimney gases. Much the same is the case with products impregnated with CCA; for example, about 80% of the arsenic compounds are released. Alternatives are either disposal at strictly controlled tips, where the substances will eventually return to nature, or combustion at very high temperatures, as in cement factories.

TRADITIONAL WOOD-BASED TREATMENTS

Wood tar is usually extracted from the parts of pine which are rich in resin: the bole and the roots. It can also be extracted from other coniferous and deciduous trees. Tar from beech is widely used in mainland Europe.

Modern extraction techniques give a very clear tar. Traditional extraction of wood tar took place in charcoal stacks and high levels of pitch and particles of carbon were included. The stack was dug out on a sloping piece of ground with the bottom shaped like a funnel and covered with birch bark. A pipe made out of a hollowed trunk was placed in the bottom of the funnel. The timber was split into sections about 18–20 cm long and 1 cm thick which were stacked radially around a strong central log. The stack was then covered with earth and turf, and lit at the bottom. The stack was allowed to smoulder for up to 24 hours, depending upon its size. The tar gathered in the funnel and could be drained off through the wooden pipe.

Wood tar can be used pure or mixed with boiled or raw linseed oil in a proportion of 1:1; pigment can also be added. Wood tar extracted from pine trees contains considerable amounts of polycyclic aromatic hydrocarbons (PAHs), for example as benzo(a) pyrene, which is a well-known mutagen and carcinogen. Tar from beech is almost free from these substances.

Bark extract is slightly toxic to insects and fungus, even though somewhat weak. It is not dangerous to humans. Bark extract has little water fastness and is most useful on exposed materials indoors. Extract based on birch bark has the best impregnating properties (see recipe on page 405–406).

Wood vinegar is corrosive and is not used preventively but for treating materials that have already been attacked by fungus and insects. Wood vinegar is extracted by distillation from deciduous trees, although even coniferous trees contain wood vinegar, but in smaller quantities.

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