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Effect of high strain-rates on the tensile constitutive response of Ecofriendly Ductile Cementitious Composite (EDCC)

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Abstract

Eco-Friendly Ductile Cementitious Composites (EDCCs) are a newly developed class of engineered cementitious composites that contains reduced amounts of cement and very high volumes of fly ash (or other SCMs) and show very high ductility and elastoplastic response in pure tension. These characteristics make EDCCs a promising material for seismic retrofit applications. This paper describes an experimental program where the effects of higher rates of loading on the tensile behaviour of EDCC are assessed. Strain-rate ratios of the orders of 103 (static to dynamic) are investigated. The rate of loading is chosen to coincide with strain-rates normally observed during earthquakes. The EDCCs tested are fiber reinforced concrete materials having a total fiber volume of 2%. Non-oiled Poly-Vinyl Alcohol (PVA) fibers and Poly-Ethylene Terephthalate (PET) fibres are used in the EDCC mixes in three different combinations: 2% PVA, 2% PET, a hybrid mix of 1% PVA + 1% PET fibers. For the quasi-static tests, a normal closed-loop test set-up is used. For the dynamic tests, a newly designed test setup using an air gun is utilized. This investigation discloses that the approximate static to dynamic ratio for the tensile strength of EDCC varies between 0.75 and 1.00 in magnitude; and, the strain capacity varies between 1.0 and 3.0 for this material. Results demonstrated that EDCCs are highly strain-rate sensitive materials and their performance during an earthquake should not be assessed from routine quasi-static tests.

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Keywords: EDCC; ECC; FRC; Eco-Friendly Ductile Cementitious Composite; Engineered Cementitious Composite; Fiber Reinforced Concrete; High Strain Rate; Tensile Strength; Dynamic Effect; Dynamic Loading; High Rates of Loading; Strain Rate Effect; Loading Rate Effect

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1. Introduction

Over the past few decades, the general use of Fibre Reinforced Concrete (FRC) has been constantly increasing within the construction industry due to its noticeable performance in terms of crack control and toughness. In fact, FRC has some great structural and non-structural applications, such as shotcrete projects, tunnel linings, or industrial type slabs on grade. One innovative type of FRC is called Engineered Cementitious Composite (ECC) which is a class of the ultra-ductile fiber reinforced cementitious composites, developed for applications in the large material volume usage generally.

During the initial development phase of EDCC, the material is tested for its mechanical properties at slow rates of loading. However, many structures could be subjected to high strain rates of loading caused by earthquakes, impacts, or blasts. In fact, EDCC is targeted to be used for seismic retrofit applications for its ductility, great toughness, and high energy absorption capacity. Thus, studying the effects of high loading rates on EDCC and how to improve its performance under these circumstances has become an important topic [1].

Generally, there are three phases in a typical FRC mix: matrix, fibre, and the aggregates. It is known that the overall impact resistance capacity of concrete is increased by introducing randomly distributed fibres into the mix. However, this capacity is limited due to the poor bonding and week interactions between the three phases within the fiber reinforced concrete. Also, the dominant failure mechanism is usually the fibre-matrix debonding caused by tensile and shear deformations. Therefore, the use of polymer and polyester fibres is more effective in increasing the energy absorption of the concrete because of their enhanced bond with the matrix [2].

When incorporated into the matrix, these fibres are also effective in reducing the weight of the concrete and enhance ductility, toughness, and crack resistance [3]. In addition, increased durability is vivid from the high fiber content mixes because of the reduction in permeability caused by the pore refinement from the addition of the fibers.

1.1. EDCC with a high volume of fly ash

EDCC (Eco-Friendly Ductile Cementitious Composite) is a new type of high performance fiber-reinforced cementitious composites (HPFRCC) with 2% volume fraction of fibre that shows high ductility. Under tensile loading, EDCC shows a relatively significant strain-hardening type behavior with great ultimate strain capacity.

Adding a high volume of fly ash to these composites helps to reduce the matrix-fibre interfacial bond strength and the matrix toughness; thus, contributing in the achievement of high strain capacities during tensile loading. This high capacity is obtained through development of multiple cracking.

The previously developed ECC is achieving the multiple cracking by using 2% volume fraction of oil coated PVA fibers [6]. However, EDCC is achieving similar capacities to ECC by 60% replacement of the cement content by fly ash and using only 1% non-coated PVA fibers in conjunction with 1% of PET fibers; whereas the conventional ECC uses pure cement with over 2% of coated PVA fibers to achieve similar performance.

This has caused EDCC to become a more sustainable as well as more economically feasible material than ECC. This type of material has many great applications such as dam repairs, bridge deck overlays, and seismic retrofits [4].

1.2. Fibers

There are two types of fibres used in the development process of EDCC: non-coated Poly-Vinyl Alcohol (PVA) fibres and Poly-Ethylene Terephthalate (PET) fibres. Below are brief introductions to these fibre types.

1.2.1. Poly-Vinyl Alcohol (PVA)

Poly-Vinyl Alcohol (PVA) fibres are produced through processing of polyvinyl alcohol which is a nontoxic, water-soluble, and fully biodegradable polymer. During this process PVA fibres are made with high crystallinity and crystal orientation, which results in them having excellent tensile strength of 0.9 – 1.9 GPa and the elastic modulus of 11 – 43 GPa. In addition, PVA fibres have high alkali resistance, good adhesive properties, and great resistivity to hot weather. Therefore, they are a very good choice of fibre to be used in FRC mixes [3].

1.2.2. Poly-Ethylene Terephthalate (PET)

Use of Poly-Ethylene Terephthalate (PET) in concrete reinforcing is a relatively new concept. These polyester fibres have a high strength and stiffness while being resistant to creep. They also have a high resistance to weathering and stress cracking. Moreover, they can be produced through chemical modifications of recycled polyethylene terephthalate plastic waste, which makes them a sustainable and cost efficient choice of fibre for use in large scale projects [5].

2. Experimental procedure

In this study four different sets of specimens are tested under high strain rate tensile loading (dynamic) and the results are then compared against the ones obtained by testing specimens with the same mix design going through quasi-static type tensile loading with very slow strain rates (quasi-static). Fig. 1 shows the sample size used.

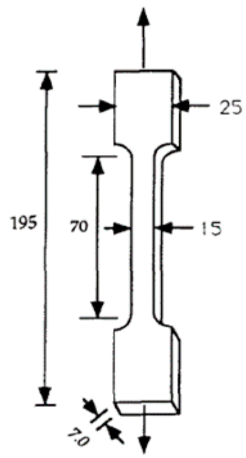

Fig. 1. Sample's dimensions (mm).

2.1. Mix designs

All the four sets of the specimens are casted using the same mix proportioning, so that the only variable would be the type of fibres used. The maximum aggregate size is 1.19 mm, passing sieve No. 16, and all the samples maintain a w/cm ratio of 0.27 and a sand/cm ratio of 0.375. As shown in Table 1, the initial set is plain concrete, followed by three other sets as: 2% PVA, 2% PET, and 1% PVA+1% PET.

Table 1. Mix designs used.

Mix Design	Cement (Kg/m3)	FA (Kg/m3)	SF (Kg/m3)	Sand (Kg/m3)	Water (Kg/m3)	PVA (%)	PET (%)
No Fibre (Plain)	390	780	78	468	337	0	0
2% PVA	385	770	77	462	333	2	0
2% PET	385	770	77	462	333	0	2
1%PVA+1% PET	385	770	77	462	333	1	1

All the mix designs resulted in concrete with unit weights of about 2050 kg/m3. Fig. 2 shows the mass proportions and compares the amount of the cementitious materials to the water and the sand used in casting the test samples.

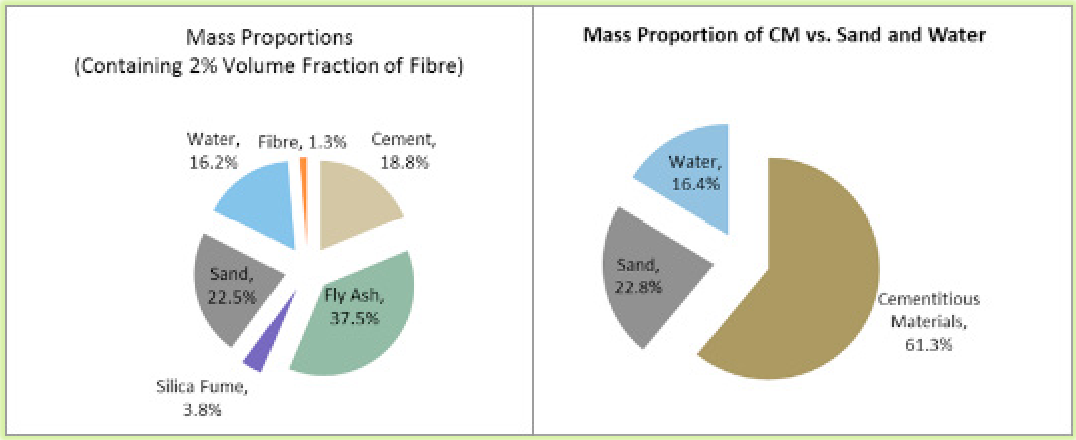

Fig. 2. Mass proportions (left); Mass proportions of CM vs. water and sand (right).

2.2. Preparing the specimens

The specimens for both dynamic and static testing are taken from the same batch of concrete in order to minimize the effect of casting conditions on the properties of the samples, to reduce uncertainties.

The ingredients are measured in small buckets and beakers using a scale with a precision of 0.1 grams. The dry ingredients including cement, fly ash, silica fume, and sand are mixed first and then a small portion of the solution of water and super plasticizer is added followed by the fibers which are added very slowly, in order to achieve a proper fiber dispersion. Finally, the remaining solution is added gradually. Fig. 3 shows the equipment used (left photo) and the measured mixture of PVA and PET fibers (right photo).

Fig. 3. Measuring and mixing equipment (left); Mixture of PVA and PET fibres (right).

EDCC is poured and evenly distributed in the molds which are pre-lubricated using light oil and consolidated using the vibrating table. The specimens are covered in plastic sheets for 24 hours in room temperature and then demolded and cured in moist room for 56 days before being tested. Fig. 4 shows the casting process including molding, consolidation, labeling, respectively from left to right.

Fig. 4. Casting, moulding, consolidation, and demoulded EDCC Specimens (from left to right).

2.3. Dynamic Tensile Testing

The tensile test is performed using a dynamic uniaxial tensile testing machine which uses the air force in a pressurized chamber to apply sudden uniaxial tensile load on the specimen which is secured by a set of special grips. Displacement is measured using a high accuracy laser sensor mounted on the specimen, monitoring the proper gage length. Thus, the only variable to adjust on the machine is the air pressure, as shown in bottom right corner of Fig. 5. Maintaining a constant high air pressure for all the specimens within a set ensures a consistent rate of loading for the specimens within that set of samples which are expected to have similar strength values.

Through various trial tests and looking at the numbers and accuracy of the recorded data, it is decided that setting the air pressure in the range of 15 – 25 psi gives a reasonable outcome for the targeted loading rate.

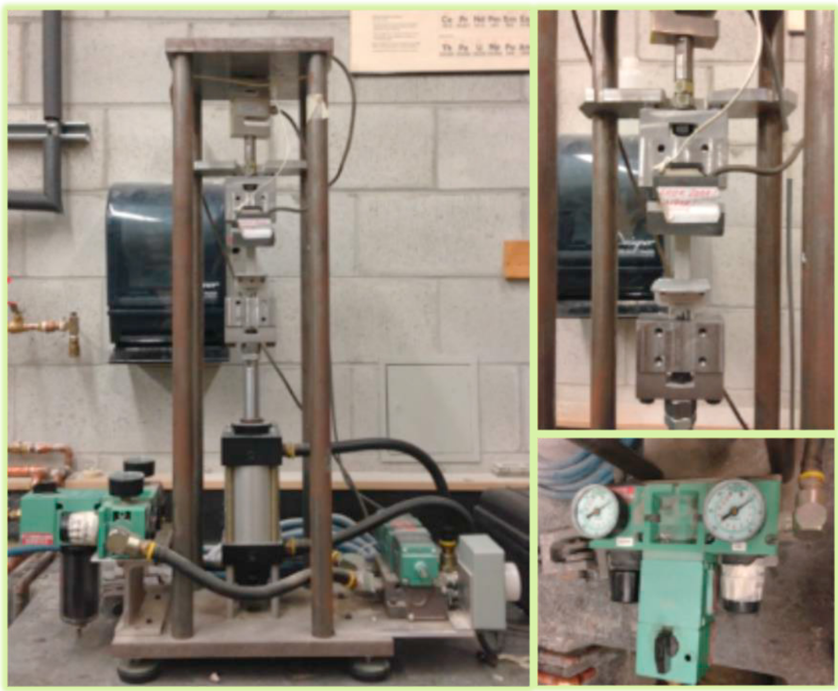

Fig. 5. Dynamic tensile loading apparatus (left), grip mechanism (top right), and the air pressure chamber (bottom right).

The samples are held firmly in place by the two custom made grips during the loading. It has been also verified that the grips do not damage the specimens prior to loading, while they do minimize slippage of the specimens when loading is taking place.

As previously mentioned, each specimen is instrumented by a laser sensor at the time of loading for displacement measurements. The laser beam emitter is mounted at the upper neck of the specimen using a special bracket. Also, a reflector plate is mounted at the bottom neck of the sample to reflect the laser rays. A digital data acquisition box precisely records the measured displacement based on the information from the laser sensor.

Fig. 5 illustrates the test setup as well as the exact locations of the laser sensor and its reflector plate, in a typical test setup. The tensile load and the distance between the laser and the bracket are recorded every 0.003 sec during the test.

In order to ensure that the measured displacement happens within the 70mm targeted gage length, any specimen which fails by a localized crack outside of the specimen neck or even at the vicinity of the boundaries of the brackets are discarded.

Fig. 6. Tested specimens (right) and the fibre pull out at the crack opening (left).

The samples usually failed as expected, at the middle of the neck, unless they are already defected or damaged at another location. Fig. 6 shows some of the samples after the test and illustrates the orientation of the fibers being pulled out at the crack opening, in a typical specimen.

3. Results

This section presents the test results obtained from the dynamic testing of the EDCC specimens under uniaxial tension. Also, the dynamic results are compared against the static results, from the previous tests. A full set of graphs are presented in the Appendix of this paper, in a larger format for reference.

Using the recorded data obtained from the dynamic tensile testing, the stress strain curves are drawn for all the tested samples. Fig. 7 shows the graphs comparing the average load-time curves (left) and the stress-strain curves (right) for all the four mix designs. The average curves are developed after data decimation, normalization, and a light filtering of the noise coming from the high sampling rate and use of the laser system.

The coefficient of variations (CV) of loads corresponding to changes in displacement are also shown in Fig. 8 for each set of the samples. These three graphs are also presented in the Appendix of this paper, in a larger format.

Moreover, the stress-strain and the load-time representative curves for each set of the samples, for the three mix designs (2% PVA, 2% PET, and 1% PVA + 1% PET), are all presented in the Appendix to show the typical graphs obtained from all the dynamic tests separately.

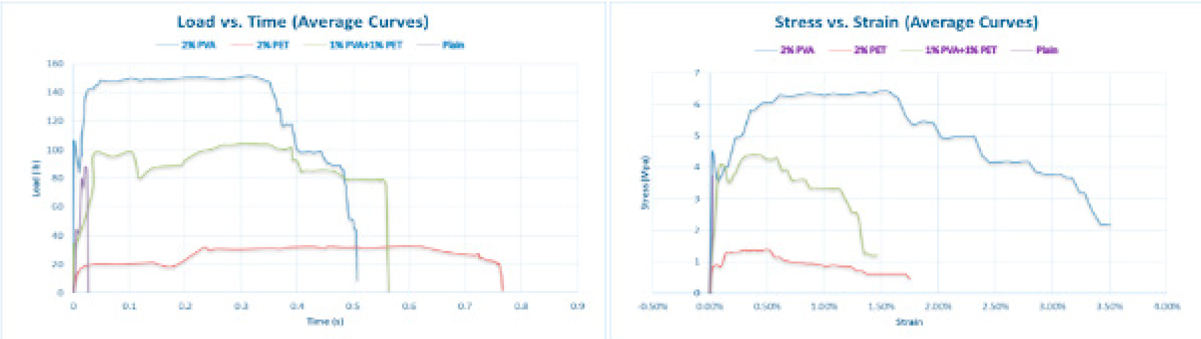

Fig. 7. Average curves for Load vs. Time (left) and stress vs. stain (right).

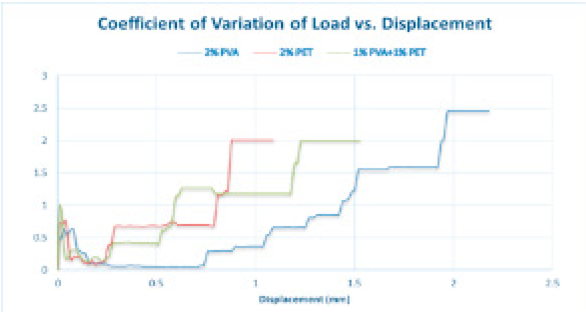

Fig. 8. Coefficient of Variation (Load vs. Displacement).

3.1. Dynamic vs. Static Tensile Testing

This section presents a series of comparative stress-strain curves in order to relate the dynamic response of the EDCC samples relative to their associated static behaviour. Fig. 9 shows the average curves comparing the stress-strain responses obtained from both quasi-dynamic and quasi-static uniaxial tensile tests for the two of the mix designs with single fibres only, either 2% PVA or 2% PET only; and, Fig. 10 shows the same response for the hybridized fiber system of 1% PET + 1% PVA fibers. For the purpose of these graphs, the samples with an average outcome are chosen from each set of samples. These graphs are also presented in the Appendix of this paper, in larger formats.

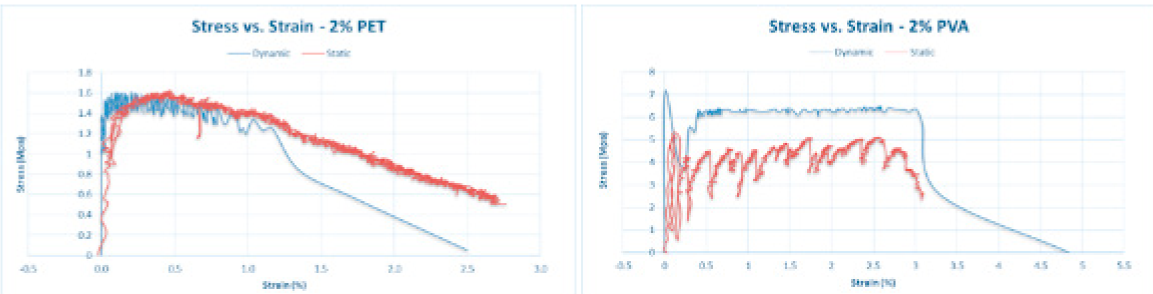

Fig. 9. Stress vs. Strain responses for the 2% PET mix (left) and the 2% PVA mix (right).

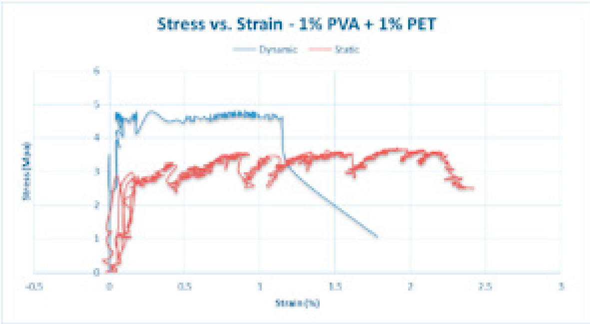

Fig. 10. Stress vs. Strain response for the hybrid mix of 1% PET + 1% PVA.

4. Discussion of the results

Based on the recorded data obtained from both dynamic and static tensile tests, for each set of samples, between 3 to 6 specimens are picked for further analysis (based on the results). The data is then used to calculate parameters to make easier comparison between the different mix designs and the two series of the tests, quasi-dynamic and quasi-static. Table 2 provides an extensive summary of the aforementioned calculated values.

Table 2. Summary of the Calculated Parameters.

	Mix Design	Stress (Mpa)		Strain		Avg Stress Rate (Mpa/sec)		Avg Strain Rate (/s)
		Max	Avg Max	Max	Avg Max	Up to Peak	Strain Hardening	
Dynamic	Plain (No Fibre)	3.75	-	0.02%	-	273.93	-	0.9374%
	2% PVA	7.45	6.78	4.84%	2.91%	419.61	25.80	6.1177%
	2% PET	1.61	1.50	1.73%	1.21%	81.300	24.37	5.1627%
	1% PVA+1% PET	5.45	4.62	1.28%	0.94%	249.36	26.61	6.0954%
Static	Plain (No Fibre)	3.13	-	0.04%	-	1.2781	-	0.0033%
	2% PVA	5.68	5.19	4.97%	3.24%	0.87488	0.1633	0.0033%
	2% PET	1.63	1.61	2.76%	2.41%	0.32573	0.1711	0.0033%
	1% PVA+1% PET	4.06	3.88	3.49%	2.45%	0.75463	0.1943	0.0033%
Ratio (static/dynamic)	Plain (No Fibre)	0.84	-	1.89	-	4.67E-03	-	3.56E-03
	2% PVA	0.76	0.77	1.03	1.11	2.08E-03	6.33E-03	5.45E-04
	2% PET	1.01	1.08	1.60	1.99	4.01E-03	7.02E-03	6.46E-04
	1% PVA+1% PET	0.74	0.84	2.72	2.59	3.03E-03	7.30E-03	5.47E-04

The maximum stress and strain values are calculated for each set, along with the associated averaged values obtained from the selected samples. In addition, the average stress and strain rates are calculated for specimens from each mix design separately. In the static tests, the strain rate is kept constant during all of the tests at 0.2% per minute (0.0033% per second). However, the rate of loading is varied amongst the specimens for the dynamic loading. Thus, specimens loaded with similar rates of loading are picked and averaged for discussion purposes.

The values of the average strain rates for the dynamic tests, and the average stress rates during the strain hardening phase for both of the tests (dynamic and static) are similar for all of the EDCC mix designs.

Among all of the three tested mix designs, the samples with 2% PVA content show higher stress and strain capacities in general. The design containing the mixture of the two fibers gives a good outcome in terms of strength while showing relatively lower strain capacities compared to the samples with only 2% PVA fibers, as expected.

The mix design containing 2% PET also result in an acceptable strain capacity, but shows a very small tensile strength, compared to other specimen types. The low tensile strength which sometimes can even be less than the samples with no fiber reinforcement, for both static and dynamic tests, can be an indication of a poor fibre dispersion in this set of samples. Some of these specimens and the corresponding results had to be discarded because of the possibility of having fiber dispersion issues in those specimens with the mixes of only PET fibers.

The last section of Table 2 provides the ratios between the values obtained from the static tests to those from the dynamic test results. The average value strain rate ratios fall within the range of 10-4 for the EDCC samples. However, in terms of tensile strength, the ratio is within the range of 0.74 to 1, and for strain capacity it varies from 1 to 2.7, depending on the fibre mixes used. Therefore, looking at these ratios we can conclude that the max tensile strength achieved is higher during dynamic loading for all the mix designs except 2% PET for which it’s slightly lower.

On the other hand, the strain capacity highly depends on the exact mix design used. In all of the samples, this capacity is generally higher for the static loading, as predicted, but for the samples with PVA fibres only, this value is relatively close for the two loadings. That is while the samples containing 2% PET fibres show a greater difference, in terms of strain, between the two tests.

5. Conclusions

For the purpose of this study, EDCC mixes containing high fly ash contents are chosen. This material, which shows some strain-hardening type behaviour, has a relatively high strain capacity under tensile loading, achieved through the well-known multiple cracking phenomenon.

After various trial tests, the fiber volume fraction of 2% is chosen as the optimum fiber content for most of the EDCC mixes, since mixes with smaller or larger amounts of fibre failed to show enhanced outcomes.

For the cases of larger volume fractions, the observed poor performance is mainly caused due to the low workability of the concrete mix. In fact, by increasing the fibre content, the workability and fluidity of the mix generally decreases. This results in poor distribution of fibres, and as a consequence, fiber dispersion related problems start to show up, causing the development of weak planes within the mortar body as well as negatively affecting the Interfacial Transition Zones (ITZ) within the cementitious matrix.

On the other hand, using lower fiber contents would also result in a weaker performance for the EDCC. In fact, there would be insufficient volume of fibers to support the load that is carried by the matrix as it cracks. Thus, multiple cracking does not occur as much and a tension-softening behaviour would replace the strain-hardening type performance consequently.

In this study, the exact same mix proportioning is utilized with three different combinations of fibres: 2% PVA, 2% PET, and 1% PVA + 1% PET. Also, a control mix, containing no fibre reinforcement, is casted from the same mix design to be tested for developing the baselines for the experiment. The samples are then tested at different loading rates and the results are compared against each other to see the effects of fiber type and the rate of loading on the overall stress and strain capacities as well as the general composite strain-stress response.

It is observed that when the strain rate goes from static to dynamic, the strain capacity of EDCC is more sensitive to the type of the fibre used compared to the corresponding tensile strength, which is more independent of the fiber type and content.

The comparison between the results also shows that when PET fibre is used in the mix design, close attention should be given to the fibre dispersion. For small sample sizes similar to the one used for the purpose of this experiment, it is very difficult to control the uniform distribution of the PET fibres within the mix. That results in a poor fiber dispersion, and consequently, a drop in the strength of the EDCC. Moreover, the study shows that PVA fibre is a better choice of fibre when it comes to the dynamic type of loading, as it shows a better overall performance.

Acknowledgements

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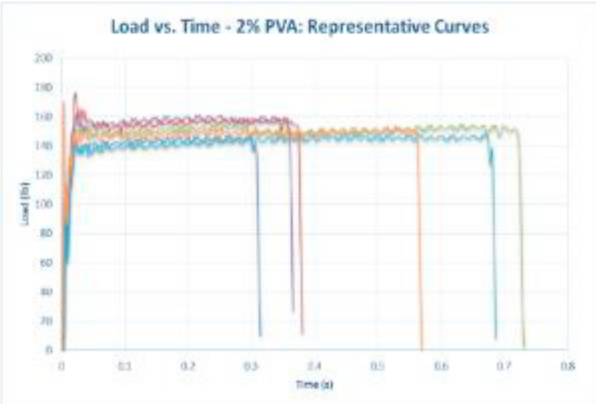
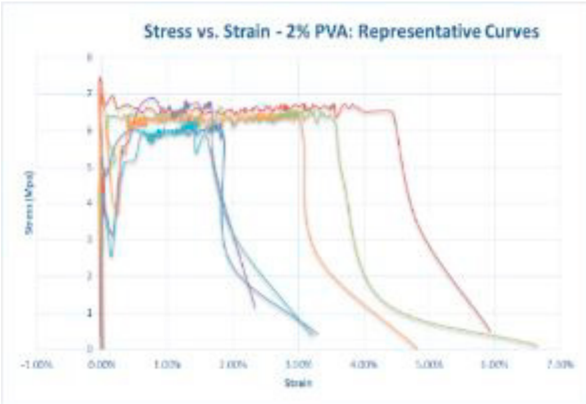
Appendix

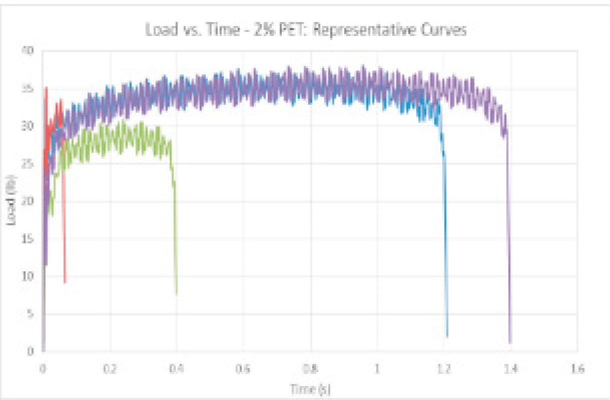
Some of the graphs presented in this appendix have already been presented within the body of the paper, in different layouts, but they are presented again here, in a larger formats, for more readability of their contents.

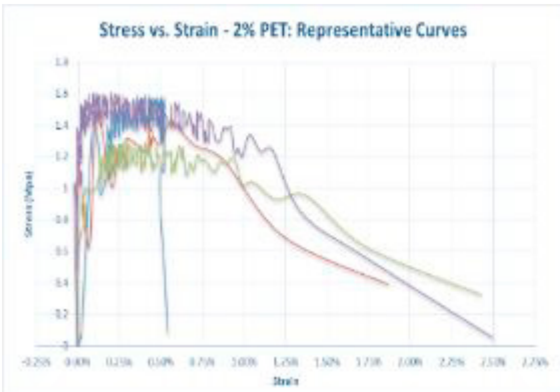
A.1. Mixes with only 2% PVA fibers



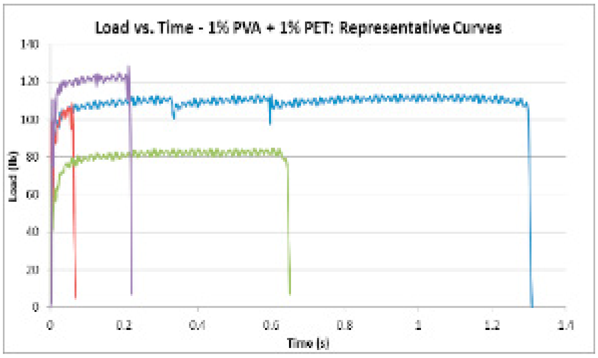


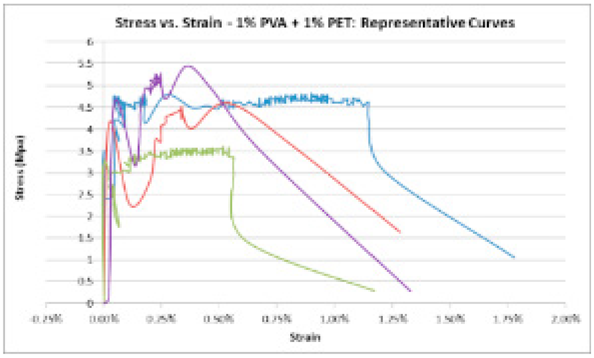
A.2. Mixes with only 2% PET fibers



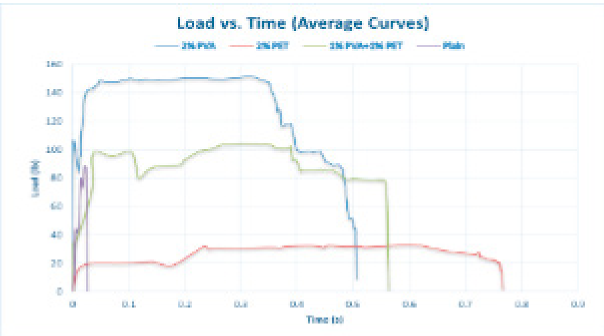


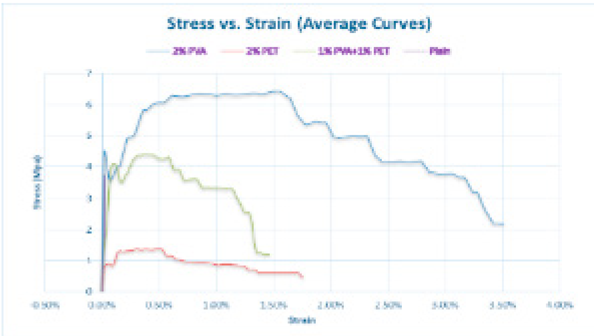
A.3. Mixes with 1% PVA + 1% PET

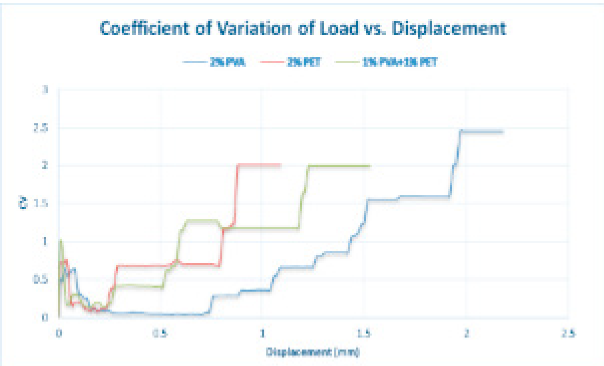


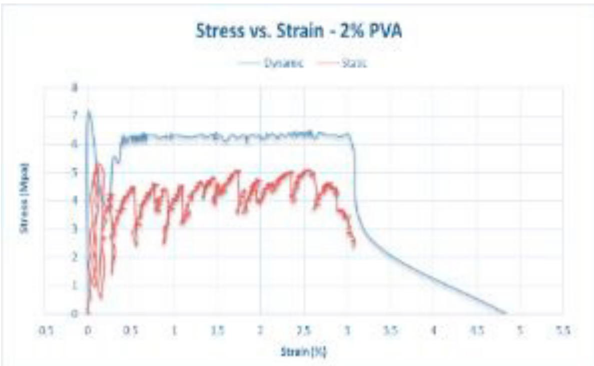


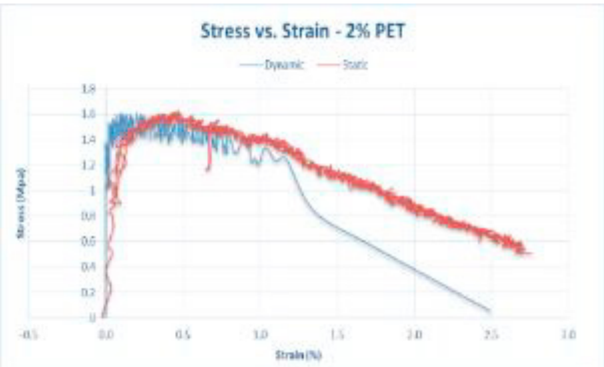
A.4. Mixes with 1% PVA + 1% PET

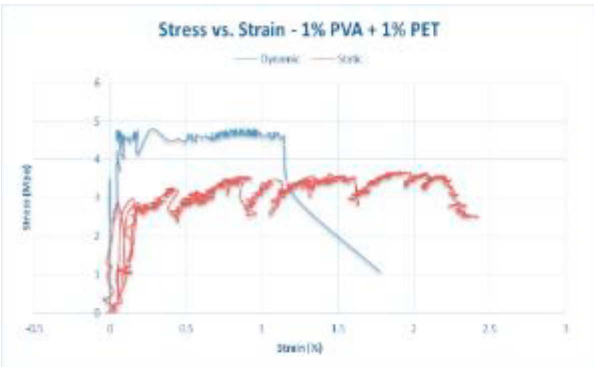












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