Effect of fiber orientation and specimen thickness on the tensile response of strain hardening UHPFRC mixes with reduced Embodied Energy

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ABSTRACT

Ultra-High Performance Fiber Reinforced Concretes (UHPFRC) have demonstrated their potential to contain the explosion of maintenance costs (Economy and Environment) for civil engineering structures, due to their extremely low permeability associated with the outstanding mechanical properties. Substitution of Embodied-Energy (EE)-costly components of UHPFRC such as clinker and steel fibers, is the next step towards sustainability, to make it even more efficient and more environment-friendly. In this study, a strain hardening UHPFRC mix with two main modifications has been developed in which (1) 75% of steel fibers have been replaced by ultra-high molecular weight polyethylene (UHMWPE, henceforth referred to as PE) fibers and (2) 50% volume of cement type CEM I have been replaced with limestone filler.
The effect of the fiber orientation and the specimen thickness on the mechanical properties of such mixes have been investigated. The mechanical properties have been investigated using direct tensile test, and 4-point bending test. Finally, the dramatic effect of fiber orientation on the ultimate strength and deformability has been demonstrated. Moreover, the results confirm that the specimen thickness affects the deformation capacity of the specimens. Finally, improvements in terms of reduction of EE of the proposed mixes, are highlighted.

Keywords: UHPFRC, Mechanical response, Strain Hardening, UHMW-PE fibers, Embodied Energy

1.   INTRODUCTION

Current UHPFRC, for structural applications in new constructions and rehabilitation of existing structures, are almost exclusively based on steel fibers. A few notable investigations have been conducted on using UHPFRC with synthetic fibers for structural applications. The synthetic fibers are mostly used in UHPFRC for facade elements with complex shapes (Chen and Chanvillard, 2012). Considering the fact that more than 50% of the EE and GWP impact of the UHPFRC is from the steel fibers contribution (Stengel and Schießl, 2008), replacing the steel fibers with synthetic fibers has a considerable effect on reducing the EE of this material.

Beginning as early as the 1990s, interest in creating a synthetic fiber reinforced concrete material with tensile ductility has been gaining ground. The first attempts to employ synthetic fibers in concrete in order to achieve a strain hardening composite were performed by Li (1993). He used micromechanics theory with the aim of obtaining evenly distributed multiple microcracks under tension, the widths of which were smaller than durability related limits. ECC (Engineered Cementitious Composite) was the result of his research; a material with PE or PVA fibers, around 4.5 MPa tensile strength and 5% strain hardening capacity.

Kunieda et al. (2007) and Kamal (2008) tried to develop a material with the advantages of both UHPFRC and Strain Hardening Cementitious Composites (SHCC), with high performance PE fibers. They achieved UHP-SHCC material with a dense matrix, significant strain hardening capacity (close to 1%), relatively high compressive strength (83 MPa) compared to normal SHCC (20.2 MPa), and tensile strength of 4.5 MPa.

This trend was continued by Ranade et al. (2013) using PE fibers in High-Strength, High-Ductility Concrete (HSHDC). They achieved an ultimate tensile strength of 14 MPa at 3.5% deformation and compressive strength of 160 MPa.

However, the tensile specimens used in all these studies were small, narrow and thin (12 mm thick and 30 mm wide in the central part), which, due to the better fiber orientation and the de-airing performance of the mix, is likely to overestimate the tensile performance compared to application with thicker (30 to 50 mm) and wider layers, which are common in rehabilitation of structural members or new constructions. In this paper, first of all, an improved cementitious material reinforced with PE and steel fibers has been developed. In order to make the new material more environmentally friendly when compared to the normal strain hardening UHPFRC, half of the cement has been replaced by limestone filler and 75% of steel fibers have been replaced by PE fibers. In the second step, the effect of fiber orientation and the specimen thickness of such mixes on mechanical properties have been investigated using direct tensile and 4-point bending tests.

2.   MATERIAL DESIGN

Packing density is the key concept for obtaining Ultra high-performance cementitious composites. Maximizing the packing density with the help of different grain classes reduces the voids in the matrix, which had to be filled with water at fresh state. Therefore, more excess water to lubricate the solid particles and enhance the workability is made available. Hence, increasing the packing density can improve the overall workability-strength performance of the cementitious material by opening up the possibility of using low W/B ratios with a wide range of fibrous mixes.

The Compressible Packing Model (CPM) (De Larrard, 1999) basically considers the energy required to compact a mix of several monosized particle classes. It also considers the loosening effect on large particles by interstitial small ones, and the wall effect within assemblies of small particles near a large one like a fiber or a container wall. Sedran (1999) generalized the CPM to consider the interaction of grain classes with arbitrary Particle Size Distributions (PSD).

In this study, the generalized CPM model was implemented in the MATLAB software. Five different powders including cement, two types of limestone filler, silica fume and

sand were used in the mixes. More than 20 mix designs were modeled. Finally, 40 x 40 x 160 mm prism specimens, of the five mixes with highest packing densities were cast in the laboratory and the final mix was chosen based on the 3-point bending performances. The mixture proportions of a normal strain hardening UHPFRC and the final mix are given in table 1 and table 2 respectively. Moreover, figure 1 shows the particle size distribution of the solid materials used in the formulation of the matrix together with that of the final mix. The packing density of the final mix is 0.78.

Table 1. A normal SH-UHPFRC mixture proportion (Denarié et al., 2011)

Component	Cement	Silica fume	Fine Sand	Water	HRWRA	Steel fiber
[kg/m^3]	1'200	150	600	200	45	353

Table 2. The mixture proportions of the final mix (PE18)

Component	Cement	Silica fume	Betocarb-SL	Betoflow-D	Fine Sand	Water	HRWRA
[kg/m^3]	547.5	191.5	183	419	589.6	178	28.7
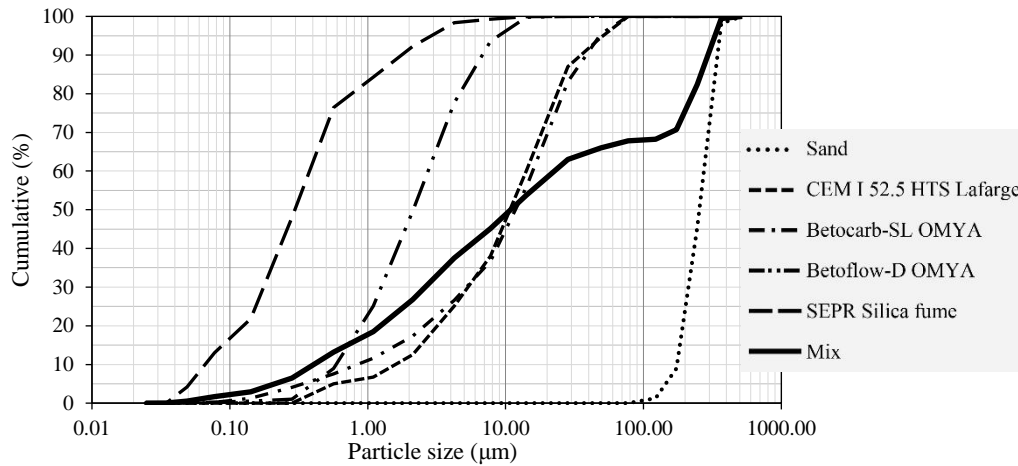
Figure 1. Particle size distribution of the components and the final mix

The fibrous mix includes 1% volume steel fiber and 2% volume PE fiber. The physical/mechanical properties and geometry of these fibers are given in table 3.

Table 3. Geometry and mechanical/physical properties of the fibers

Type	Volume fraction	Diameter	Length	Elastic Modulus	Tensile strength	Specific gravity
	[%]	[µm]	[mm]	[GPa]	[MPa]	
Steel	1	200	10	200	2000	7.85
UHMPE	2	16	10	130	3000	0.97

Table 4 shows the 3-point bending performance and compressive strength of the final mix. After casting, the specimens were sealed with a plastic cover for 4 days at room temperature of 20 ± 5°C. This was followed by an elevated thermal curing for 3 days at 85°C under 95 % RH. The specimens were then kept unsealed at room temperature of 20 ± 5°C before testing at 14 days.

*Table 4. The average MOR and compressive strength of 40 x 40 x 160 specimens*

MOR [MPa]	Compressive strength [MPa]
30.6	170.4

3.   EXPERIMENTAL PROGRAM

3.1   Specimen preparation

The experimental program was designed in a way to investigate the effect of fiber orientation as well as specimen thickness on the mechanical properties.

- Inspired from Wuest et al. (2009) and Ferrara et al. (2011), in order to study the fiber orientation effect, two square plates of 580 x 580 x 30 mm were cast with the material poured from one end to the other, without joints. Figure 2a illustrates the casting procedure. Afterward, three dumbbell specimens (560 mm long) for the direct tensile test and two 500 x 100 mm specimens for the 4-point bending test were cut from each plate with a waterjet machine; one set parallel to the direction of casting and the other set perpendicular to the direction of the casting. Figure 2b and 2c show the position of the specimens that were cut from the 580 x 580 mm plates. In order to avoid surfacing, the top surfaces of the two plates were covered immediately after pouring with a wood panel to which Controlled Permeability Formliner (CPF) - Zemdrain® sheets were attached, to guarantee a flat and uniform upper surface after setting.
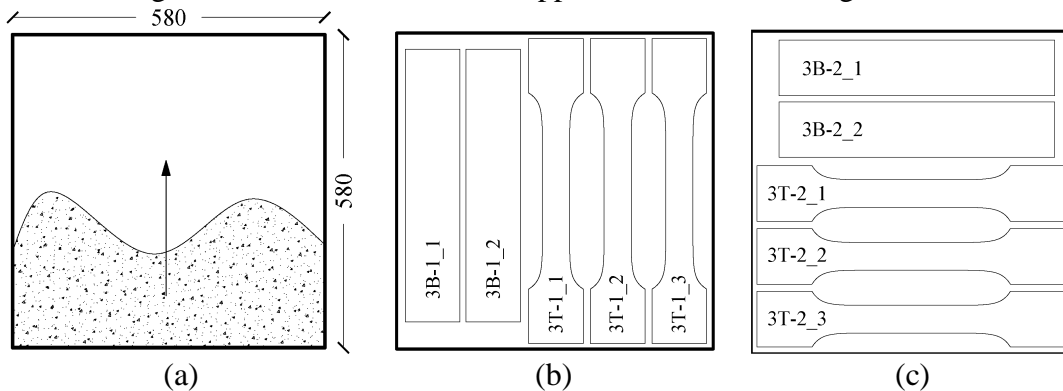

Figure 2. the specimens to study the fiber orientation effect; (a) the casting direction, (b) the specimens parallel to the casting direction and (c) the specimens perpendicular to the casting direction

- With a view to investigating the effect of specimen thickness on the mechanical properties, three specimens of 500 x 200 x 50 mm and three specimens of 500 x 200 x 10 mm were cast. From each of them, one dumbbell specimen (490 mm long) and one 490 x 95 mm specimen were cut with waterjet for the direct tensile and 4-point bending tests respectively.

To limit as far as possible the stress concentrations, Neuber's (1969) solution was adapted to the geometry of the dumbbell specimens. There are three types of tensile specimens with geometry and gauge length as shown in figure 3. Type I is 560 mm long, 30 mm thick and 50 mm wide. It has one LVDT at each side (4 in total) in order to check the eccentricities in both directions to avoid bending effects while loading. The gauge lengths of the LVDT are 300 mm and 200 mm for this specimen. Type II is 490 mm long, 50 mm thick and 50 mm wide, with the similar installation of LVDTs as the specimen type I, and with the gauge lengths of 345 mm and 220 mm in opposite directions. Type III is 490 mm long, 10 mm thick and 50 mm wide and has two LVDTs in one direction with a gauge length of 220 mm.

Thermal curing was applied to all specimens. The specimens were sealed after casting with plastic for 4 days at room temperature of 20 ± 5°C. This was followed by elevated thermal curing for 3 days at 85°C under 95 % RH. The specimens were then kept unsealed at room temperature of 20 ± 5°C before testing at 14 days.
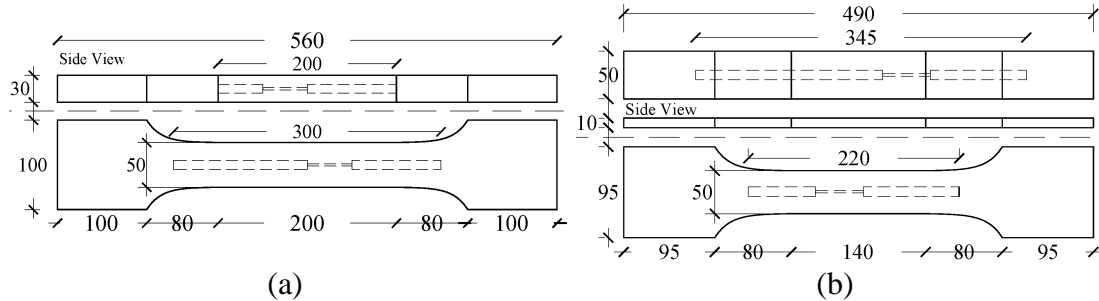
Figure 3. The dumbbell specimen geometry for the tensile testing (a) specimen type I and (b) specimens type II and III (all dimensions in mm)

3.2   Experimental setup

Direct tensile tests were performed under quasi-static uniaxial loading under displacement control with a stroke rate of 0.4 mm/min. The dumbbell specimens were gripped on their faces in a fixed-fixed type of end constraints using hydraulic clamping system.

The 4-point bending tests on the plates were done following Denarié (2015). The tests were performed under displacement control at a stroke rate of 0.5 mm/min. The support span of flexural loading was 420 mm and the loading span was 140 mm. The force was measured by the load cell of the testing machine, and the mid-span deflection was recorded using two LVDTs placed at mid-span, attached to a measuring frame fixed to the middle axis of the specimen, on the support points, during the test.

4.   RESULTS AND DISCUSSION

4.1   Fiber orientation effect

The results of the direct tensile tests on dumbbell specimens that were cut parallel and perpendicular to the direction of casting are presented in figure 4. The results are presented in the stress-displacement format in order to be able to show the post-cracking behavior. The gauge length for this set of data is 300 mm.

As the results show, the fiber orientation has a strong effect on the mechanical properties of the material. The ultimate strength of the specimens that were cut perpendicular to the casting direction is reduced by around 30% and the deformation capacity is decreased by around 50% when compared to that of the specimens cut parallel to the casting direction. Increasing the fibers inclination angle with respect to the direction of principal stresses, reduces their overall performance in the composite and thus decreases its ultimate strength as well as its deformability; for stiff fibers and likewise also for flexible ones.

The 4-point bending behavior of the two types of specimens is presented in figure 5. According to this set of data, the results of the 4-point bending tests follow the same trend as that of the direct tensile tests on ultimate strength and deformability, and soundly confirm the important effect of fiber orientation on the mechanical properties of these materials.
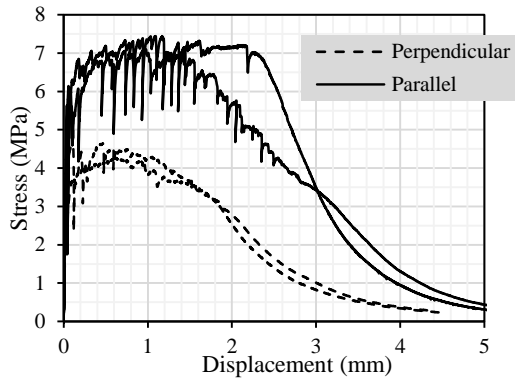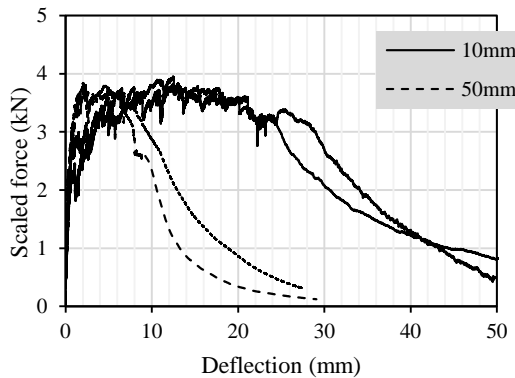
Figure 4. direct tensile test results of dumbbell specimens cut parallel and perpendicular to the casting direction (gauge length is 300 mm)
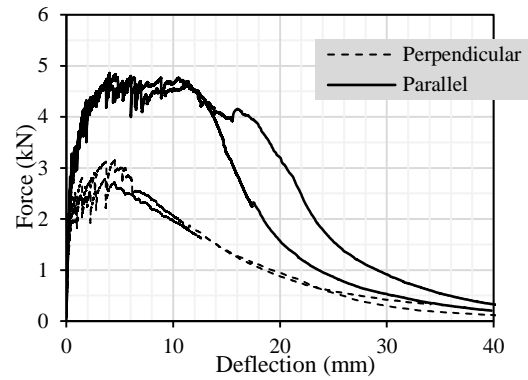

Figure 5. 4-point bending behavior of 500x100x30 plates that were cut perpendicular and parallel to the casting direction

4.2   Specimen thickness effect

The 4-point bending responses of the 10 mm and 50 mm thick specimens are shown in figure 6. In this figure, the force is scaled so that it is comparable with the results of the 30 mm thick specimens, by multiplying the actual force by $(30/\text{specimen thickness})^2$, as the bending strength is expected to vary with the square of the specimen height.

The deformability of the specimens is increased by decreasing the thickness whereas the ultimate load is not affected. Additionally, the results of the direct tensile tests, which are presented in figure 7, fairly verify this trend. The position of the extent of the hardening zone is shown with vertical lines for each specimen thickness in this figure.

Figure 6. 4-point bending behavior of 10 mm and 50 mm thick plates
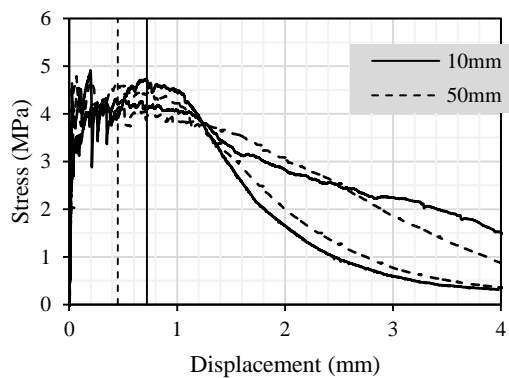
Figure 7. direct tensile test results of 10mm and 50mm thick dumbbell specimens (gauge length is 220 mm)

Regarding the ultimate strength, decreasing the specimen thickness reduces the distance that an air bubble has to travel in order to leave the fresh material. Thus, the thinner specimens should generally show a higher mechanical performance due to their less void content. However, in this case, it seems that the dense network of the PE fibers entraps the air bubbles and slows down the de-airing of the material at the

fresh state. In addition, no obvious difference can be seen between the bottom surface of the specimens with 10 mm and 50 mm thick. Accordingly, assuming that decreasing the thickness does not improve the de-airing behavior of such a material, it can be concluded that the specimen thickness does not affect the ultimate strength of such mixes to a large extent.

5.   CONCLUSIONS

− A SH-UHPFRC mix with reduced Embodied Energy has been developed in which, 50% of cement is replaced by limestone filler and 75 % of steel fiber is replaced by PE fibers.
− After Table 5, 60% reduction in the EE in the new mix compared to a normal strain hardening UHPFRC as well as reduction of 300 kg/m^3 in the dead weight of the material were achieved.

Table 5. Comparison of EE between a normal SH-UHPFRC and the new mix

		SH-UHPFRC	New mix
Total EE	[MJ/m^3]	28'830	11'390
Specific weight	[kg/m^3]	2'550	2'250

− Fiber orientation and specimen thickness have a considerable effect on the mechanical properties. The specimen thickness mostly affects the deformability of the specimen. Likewise, the fiber orientation affects the ultimate strength as well as deformation capacity.
− Currently, most of the research results in the field of PE fiber reinforced cementitious material are based on the JSCE (2008) tensile specimen preparation methodology. This methodology with a thin and narrow (12 mm thick and 30 mm wide) specimen overestimates the tensile performance of the material, with respect to its potential performance in structural applications wherein less favorable fiber orientation is encountered.

6.   ACKNOWLEDGMENTS

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