Tensile characterization of a "eco-friendly" UHPFRC with waste glass powder and sand

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ABSTRACT

A new type of ecofriendly ultra-high-performance glass concrete (UHPGC) was developed at the Université de Sherbrooke using waste glass with varying particle-size distributions (PSD). The compressive strength was higher than 150 MPa and mini-slump spread diameter higher than 250 mm (which resulted into a good self-compacting ability of the fluid mixture).
This paper presents the characterization of the tensile behavior of this advanced cementitious composite, since the post-cracking tensile performance is a fundamental mechanical characteristic of ultra-high-performance fiber-reinforced concrete (UHPFRC). Two UHPGC with different compositions were investigated in this study: one mixture containing glass powder as a cement replacement material and the other mixture containing glass powder and glass sand as a replacement of both binder and fine aggregates. Both mixtures contained 2% by volume of micro steel fiber with aspect ratio equal to 65. Two curing regime were used (hot curing and normal curing) and the effect of this different curing regime on the tensile behavior has been also investigated. A total of six sets of specimens were tested at different ages, equal to 28 and 91 days respectively, including, as a further experimental variable, the flow-induced alignment of the fibers. A novel experimental technique, called Double Edge Wedge Splitting Test (DEWS), recently developed at Politecnico di Milano, was employed to characterize the material tensile response. This is an indirect tensile test technique, in which a compressive load applied to the specimen is able to result into a tensile stress state over a critical ligament section suitably highlighted thanks to specimen geometry and loading set-up. The DEWS test is able, as demonstrated, to provide straightforwardly the tensile stress vs. crack opening response of the cementitious composite with no need for back analysis. The results highlight the possibility of obtaining a strain-hardening composite, also exploiting the favorable alignment of the fibers, and hence to produce a UHPFRC with significant sustainable signature, employing considerable amounts of waste material as cement and natural aggregate replacement.

Keywords: Ultra-high-performance glass concrete (UHPGC), waste glass, tensile behavior, fiber orientation.

INTRODUCTION

The construction industry is increasingly concerned about the environment, aiming at building as environmentally friendly as possible, minimizing environmental impact. Hence, new sustainable building materials are being developed. From an environmental point of view, one of the main objectives is to reduce CO_2 emissions, which could be achieved by reducing the use of cement in the production of concrete (Fantilli et al. 2016).

So far, new sustainable building materials called eco-friendly cement-based composites are being developed which reduce the environmental impact compared to traditional concretes. The aim of these materials is to replace a part of the cement with waste materials to enhance the environmental efficiency reducing the environmental impact of the concrete (Marinkovic et al. 2016). Using glass powder (GP) as a partial replacement of cement minimize the environmental impact by reducing CO_2 emissions (Soliman et al. 2016). Besides sustainability, using glass powder instead of cement, also improves durability characteristics due to the improved properties of the pore network, such as reduction of chloride-ion penetration into concrete (Omran et al. 2016).

Ultra-high-performance glass concrete (UHPGC) is an innovative type of UHPC that constitutes a breakthrough in sustainable concrete technology, (Tagnit-Hamou, A., and Soliman, N., 2014) as it comprises granulated post-consumer glass with a specific particle-size distribution (PSD) developed using glass sand, high amounts of glass powder, and moderate contents of fine glass powder. UHPGC technology can provide ecological benefits by valorization of post-consumer glass and reducing the CO2 footprint of UHPC. It can also provide economic benefits by reducing the volume of land-filled materials and lowering the cost of UHPC. While UHPGC can be designed with less cement, SF, QP, and QS than typical UHPC, it still contains fibers and a high-range water-reducing admixture (HRWRA). UHPGC can be produced with low water binder ratio (w/b), yet because the glass particles have zero absorption, its rheological properties allow it to be practically self-placing. Depending on UHPGC composition and curing temperature, the concrete's compressive strength was higher than 150 MPa and mini-slump spread diameter higher than 250 mm (which resulted into a good self-compacting ability of the fluid mixture).

From a mechanical point of view, the ultra-high-performance glass concrete (UHPGC) present herein has also a good mechanical behavior with the possibility to reach high compressive strength values. If fibers are added into the concrete mix, the ductility and flexural behavior also improves due to the crack-bridging effects provided by fibers which gives a well-controlled crack propagation (Cuenca et al. 2010, 2015, 2017a, 2017b), (Echegaray-Oviedo et al. 2013). To quantify the toughness and tensile behavior of these fiber-reinforced cementitious materials suitable characterization tests are needed.

Usually the tensile response of these materials is indirectly investigated the use of flexural tensile test methods for UHPC and the associated analyses necessary for appropriate interpretation of the results. These analyses, often referred to as inverse analyses, derive the uniaxial tensile response from the observed load, deflection, and possibly surface strains observed during a flexure prism test (Baby et al. 2013). A four-point flexural test method based on ASTM C1609 had been utilized for use in determining the uniaxial tensile response of UHPGC accompanied with necessary inverse analysis based on bending moment versus midspan deflection experimental response.

In addition to, a novel experimental testing technique, called Double Edge Wedge Splitting Test (DEWS) recently developed at Politecnico di Milano (Di Prisco et al 2013) allows to identify the tensile "constitutive" behavior of the cementitious composite without performing any back analysis. The DEWS test is an indirect tensile test performed on specifically designed specimens that due to their geometry and the loading set-up is able to induce a pure mode I fracture mode along the ligament. Since the ligament can be "predetermined" through notches, this also allows to analyze the influence of the orientation of fibers with respect to the crack. In fact, it is essential that the orientation of fibers match as close as possible with the direction of the principal tensile stress within the element when in service, so to achieve a more efficient structural use of the material (Ferrara 2015a, 2015b).

EXPERIMENTAL TESTS: DESCRIPTION AND RESULTS

The experimental program included performing of four-point flexural tests based on ASTM C1609 on six sets of UHPGC specimens, Double Edge Wedge Splitting Test (DEWS) on twelve sets of UHPGC specimens and other associated tests, such compressive and modulus of elasticity tests. Two UHPGC with different compositions were investigated in this study: one mixture containing glass powder as a partial replacement of cement and full replacement of quartz powder while the other mixture containing glass powder as a partial replacement of cement and full replacement of quartz powder in addition to glass sand as a partial replacement of quartz sand. The materials used to produce the two mixture are described in the next section. Both mixtures contained 2% by volume of micro steel fiber with aspect ratio equal to 65. The curing regime applied to the UHPGC was also a variable, whereas two different curing regime were applied (hot curing and ambient laboratory curing). The specimens which cured at ambient laboratory were tested at different ages 28 and 91 days. The mixtures considered in this test program all had compressive strengths ranging from 115 to 165 MPa, modulus of elasticity ranging from 40 to 44 GPa (see Table 2), and slump flow equal to 750, 800 mm for mixture 1 and mixture 2 respectively.

Materials

As with any concrete or mortar, UHPC rheology is strongly affected by cement fineness as well as the two most reactive components in Portland cement—C_3A and C3S. The cement characteristics are even more critical in the case of UHPGC, as the very low w/b results in close packing of the cement particles. It is particularly important to select cement with the lowest contents of C3A and C3S. The cement selected was formulated with a low C3A amount to provide high sulfate resistance. The cement properties included: Bogue composition of 50% C_3S, 25% C_2S, 14% C_3A, and 11% C_4AF; specific gravity of 3.21; Blaine fineness of 370 m^2/kg; and D_{50} of 11 μm. Other materials used in the UHPGC mixture included:

• Silica fume (SF) compliant with CAN/CSAA3000-13 "Cementitious materials compendium" specifications with silica content of 99.8%, specific gravity of 2.20, D_{50} of 0.15 μm, and specific surface area of 20,000 m^2/kg;

• Quartz sand (QS) with silica content of 99.8%, specific gravity of 2.70, D_{50} of 250 μm, and maximum particle size of 600 μm;

• Glass powder (GP) with silica content of 73%, specific gravity of 2.60, maximum particle size of 100 μm, and Na_2O content of 13%;

• Polycarboxylate-based HRWRA, marketed as ViscoCrete-6100 (Sika); and

• Micro steel fibers with 13 mm (0.5 in.) length and 0.2 mm (0.008 in.) diameter.

Concrete mixture

The mixture design was developed in three steps (Soliman, N., et al. 2016). In the first step, the packing density of the granular composition (QS, GP, GS, cement, and SF) was optimized to 0.78% using the compressible packing model. The resulting mixture comprised 410 kg/m3 of GP. In the second step, the optimum HRWRA dosage was determined for a range of w/b values, yielding the rheological characteristics needed to obtain a self-consolidating matrix as well as adequate strength. In the third step, the fiber content was optimized as needed to improve the UHPGC ductility without significantly altering the rheological properties of the fresh mixture. Table 1 provides the compositions for the UHPGC mixtures with w/b of 0.225 used in this project.

Table 1: UHPGC mix design

Material	Mixture1 Kg/m^3	Mixture2 Kg/m^3
Type HS cement (C)	560	560
Silica fume (SF)	210	210
Quartz powder (QP)	-----	-----
Glass powder (GP)	410	410
Water	226	226
Steel fiber	156	156
Quartz sand (QS)	898	449
Glass sand (GS)	-----	449

HRWRA (solid content)	17	17

Table 2: UHPGC Material Properties

Specimen Set	Mixture ID	Compressive strength (MPa)	Elastic modulus (GPa)
GP_ 28d	Mixture 1	120	42
GP _91d	Mixture 1	145	43
GP _HC	Mixture 1	165	44
GP+GS_ 28d	Mixture 2	115	40
GP+GS _91d	Mixture 2	140	41
GP+GS _HC	Mixture 2	150	42

Note: GP (glass powder); GS (glass sand)

Flexural Performance

As mentioned before the flexural tests were performed according to ASTM C1609. All prisms had a 100 mm by 100 mm cross section and 400 mm length. Prisms were cast in open-top steel forms by pouring the UHPGC into the form at one end then allowing it to flow toward the other end.

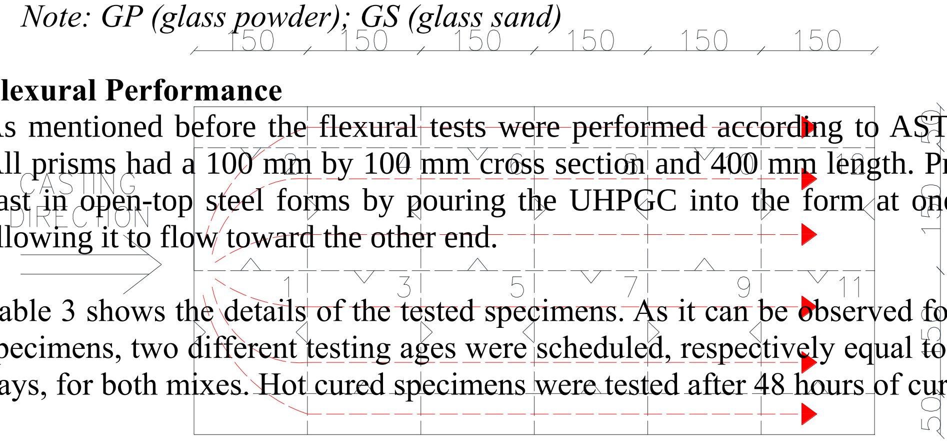


Table 3 shows the details of the tested specimens. As it can be observed for air cured specimens, two different testing ages were scheduled, respectively equal to 28 and 91 days, for both mixes. Hot cured specimens were tested after 48 hours of curing.

Table 3. Details of flexural test specimens.

Specimen Set	No. of specimens	Mixture ID	Curing regime
GP_ 28d	2	Mixture 1	NC (28 days)
GP _91d	2	Mixture 1	NC (91 days)
GP _HC	2	Mixture 1	HC (48 hours)
GP+GS_ 28d	2	Mixture 2	NC (28 days)
GP+GS _91d	2	Mixture 2	NC (91 days)
GP+GS _HC	2	Mixture 2	HC (48 hours)

Note: NC (normal curing); HC (hot curing)

The load versus the deflection for all specimens were recorded. Then the flexural stress vs. deflection were plotted for all specimens as shown in Figure 1.

From these curves, we can notice that the two mixtures behave elastically up to the first crack then a region of strain hardening with multiple cracks were started up to the modulus of rupture followed by a region of crack opening with softening behavior. The two mixture have almost the same first cracking strength ranging from 13 to 15 MPa for different curing regime and different testing ages, in addition to, modulus of rupture ranging from 20 to 25 MPa for different curing regime and different testing ages In addition to , we can observe that Mixture 2 with GP and GS have better flexural performance especially in terms of toughness and dissipated energy than Mixture 1 and this may be due to better rheological performance which lead to better dispersion of fiber (Weina M., Kamal H. Khayat 2017).

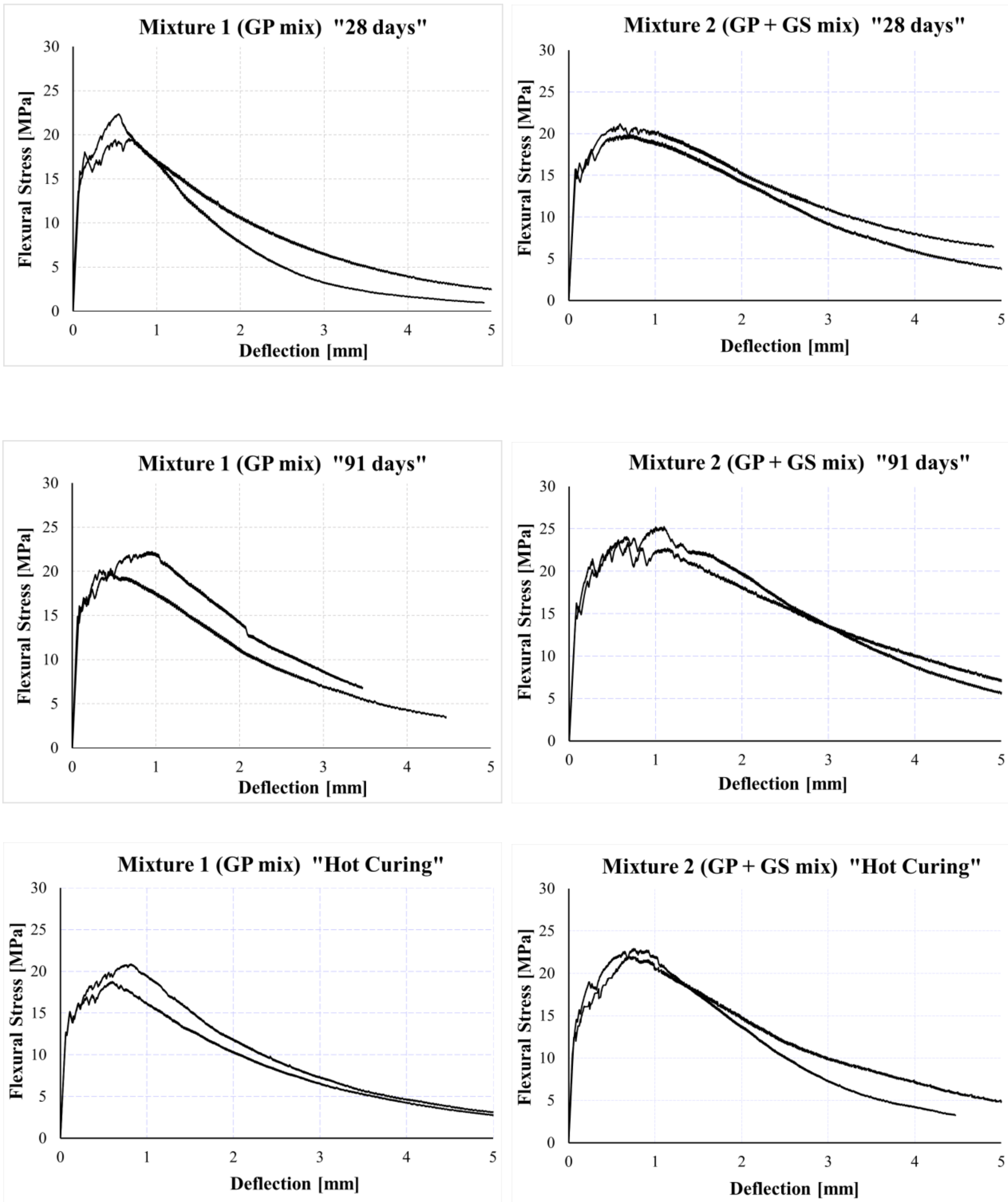


Figure 1. Flexural Stress -Deflection curves for all specimens

Tensile behavior

In order to identify the influence of the fiber alignment on the tensile behavior of UHPGC, two slabs were cast according to the casting procedure schematically shown in Figure 2. One slab was cast with mixture 1 and the other one with mixture 2. The slab dimensions were 0.9 m long, 0.4 m wide and 25 mm thick. Then twelve specimens for (DEWS) were extracted from each slab.

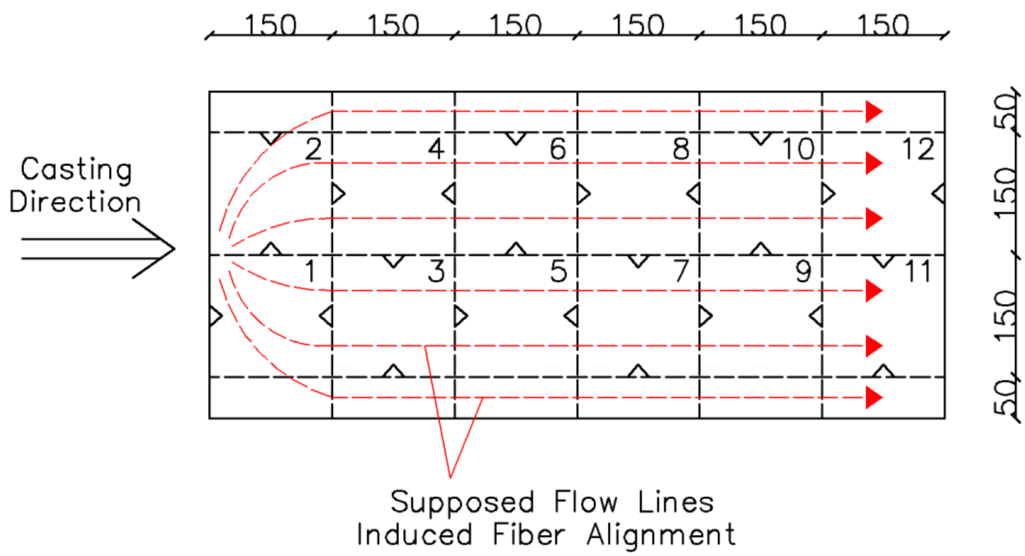


Figure 2. Schematics of slab casting and of DEWS specimen cutting for tests featuring flow-driven orientation of fibers

The tensile behavior of the advanced cementitious composites described above was also analyzed with a novel experimental testing technique, called Double Edge Wedge Splitting Test (DEWS), developed at Politecnico di Milano (Di Prisco et al. 2013).

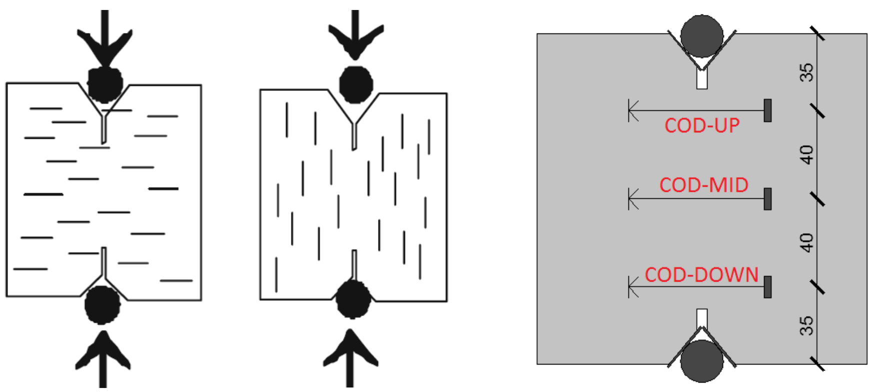
Table 4 provides a synopsis of the DEWS tested specimens. As it can be observed for air cured specimens, two different testing ages were scheduled, respectively equal to 28 and 91 days, for both mixes. Hot cured specimens were tested at 61 days since no significant effect of longer aging was expected herein of the same high temperature curing.

Each specimen had the following nominal dimensions: 150x150x25mm. Due to the suitably conceived notched specimen geometry when cutting specimens, it was possible to predetermine the fracture plane in specimens and hence, which allowed to decide the orientation of the flow-induced preferential alignment of fibers with respect to the fracture plane (perpendicular or parallel), as shown Figure 3 (a).

Table 4. Details of (DEWS) specimens.

Specimen Set	*No. of specimens*	*Mixture ID*	*Curing regime*	*Alignment of fibers with respect to the crack*
GP_28d	2	Mixture 1	NC (28 days)	Parallel
GP_28d	2	Mixture 1	NC (28 days)	Perpendicular
GP+GS_28d	2	Mixture 2	NC (28 days)	Parallel
GP+GS _28d	2	Mixture 2	NC (28 days)	Perpendicular
GP _HC	2	Mixture 1	HC (48 hours)	Parallel
GP _HC	2	Mixture 1	HC (48 hours)	Perpendicular
GP+GS _HC	2	Mixture 2	HC (48 hours)	Parallel
GP+GS _HC	2	Mixture 2	HC (48 hours)	Perpendicular
GP _91d	2	Mixture 1	NC (91 days)	Parallel
GP _91d	2	Mixture 1	NC (91 days)	Perpendicular
GP+GS_91d	2	Mixture 2	NC (91 days)	Parallel
GP+GS_91d	2	Mixture 2	NC (91 days)	Perpendicular

Note: GP (glass powder); GS (glass sand); NC (normal curing); HC (hot curing)



(a) **(b)**

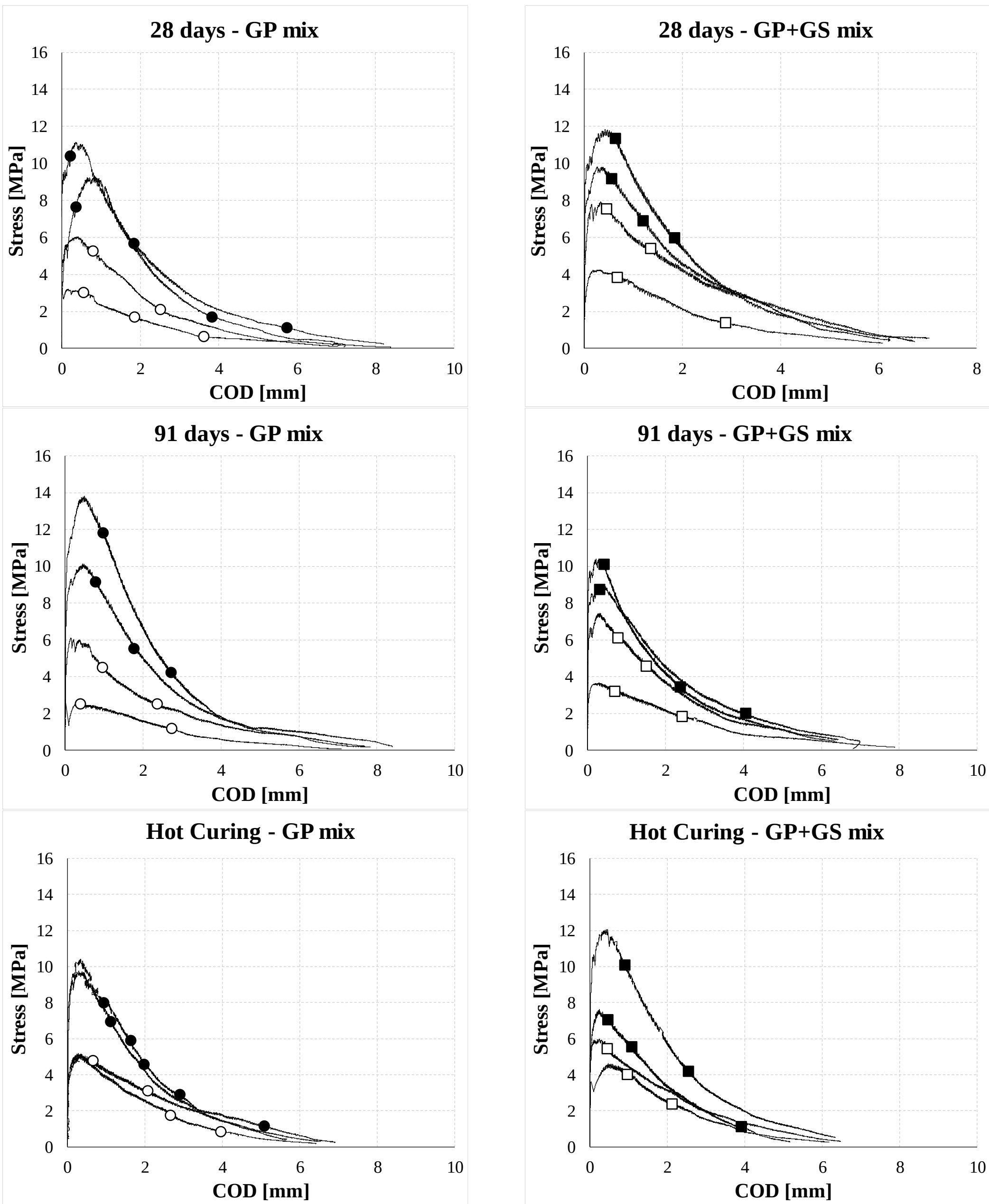
Figure 3. Main alignment of fibers (a) and test set-up (b)

In order to facilitate the identification and further analysis of each specimen, a specimen identity (Specimen ID) was assigned as shown in Table 4.

After the curing periods, 28 and 91 days respectively, specimens were cracked and tested until failure by means of the "Double Edge Wedge Splitting" test methodology (Di Prisco et al. 2013).

Tests were performed controlling and measuring the Crack Opening Displacement (COD) across the ligament on both the front and rear faces of each specimen (Figure 3b).

As expected, specimens with a favorable alignment of fibers (fibers perpendicular to the fracture plane) reached the highest loads and stresses compared to those with an unfavorable fiber orientation. This occurred for the three different curing periods. Focusing on specimens with a favorable fiber orientation is observed that both mixes reached similar peak stress values, except for the specimens tested after 91 days of curing. In this case, specimens with finer glass powder as cement replacement (GP mix) reached the highest stress values which means that finer glass particles possess an explicit some kind of pozzolanic reactivity with age (Figure 4).



● Mix with glass powder (GP) – fiber with perpendicular alignment

○ Mix with glass powder (GP) – fiber with parallel alignment

■ Mix with glass powder and glass sand (GP+GS) – fiber with perpendicular alignment

□ Mix with glass powder and glass sand (GP+GS) – fiber with parallel alignment.

Figure 4. Load-COD curves for all curing periods

Inverse analysis

To derive the tensile stress-strain relationships from four-point flexural tests, two inverse analysis methods were done.

The first method is a simplified five-point inverse analysis method. This method is based on the determination of only five key points in experimental bending strength vs. displacement at mid-span curves and in the application of a back-of-the-envelope calculation to define normalized stress – strain behavior (Juan Angel Lopez et al. 2016) the global process of this method is shown in figure 5.

The second method is point by point inverse analysis. In this method, the curvature in the constant bending moment zone is derived from the "Bending moment vs. mid-span deflection experimental response" through an equation which relates the mid-span deflection of the prism to the curvature along the middle third of the span. (Qian, S., and Li, V. C., 2008). This equation is based on structural elastic mechanics and considered as reasonably valid for nonlinear behavior. The method is based on the equilibrium of moments and forces in a sectional analysis for each value of curvature (Baby F et al. 2012), (Rigaud, S. et al. 2011). The global process of this method is shown in Figure 6. The analysis results and the comparison with DEWS test results are shown in Figure7.

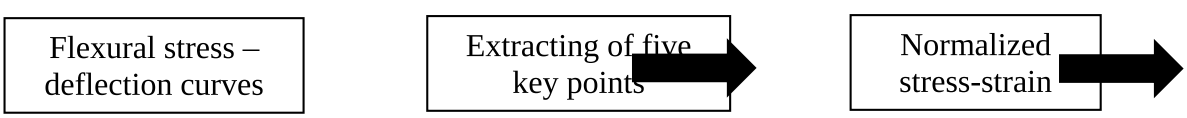


Figure 5. Global process used for the simplified five points inverse analysis method based on deflection measurement

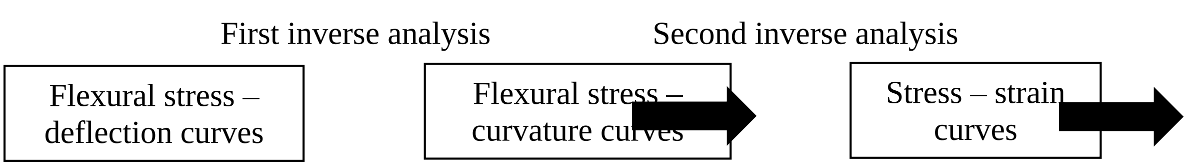


Figure 6. Global process used for point by point inverse analysis method based on deflection measurement

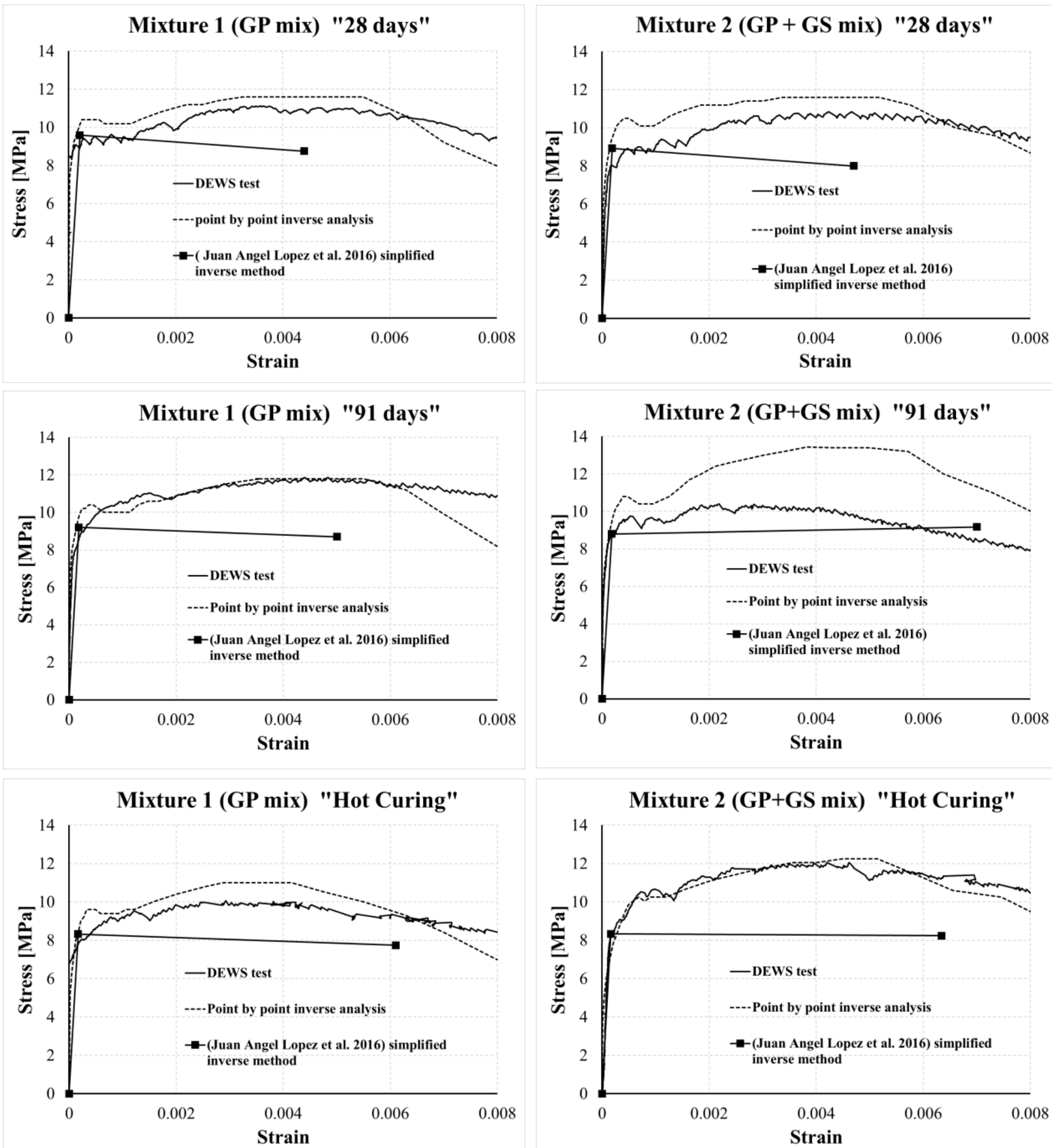


Figure 7. Tensile stress- strain relationships obtained from DEWS tests, point by point inverse analysis and (Juan Angel Lopez et al. 2016) simplified inverse method

Analysis of results

From Figure 7, it is observed that point by point inverse analysis method slightly overestimate the strength with deviation equal to about from 2 to 6% than DEWS. The uniaxial stress – strain behavior of UHPGC in tension can be divided into four main phases: I: Elastic phase, II: Multi cracking phase, III: Crack straining phase, IV: localized phase. The idealized UHPGC uniaxial tensile behavior through this test program was illustrated in Figure 8. These phases refer to the behavior that occur through the uniaxial straining of the UHPGC. Phase I, the elastic phase, refers to the elastic straining of the section until the first cracking strength. Phase II, the multi cracking phase, refers to the part of the behavior wherein the specimens repeatedly crack within the gauge length. This phase is characterized by a nearly constant stress level. Phase III, the crack-straining phase, is the part of the behavior characterized by increasing crack opening as the fiber reinforcement goes through a combination of elastic straining and debonding. The final phase, localization, is characterized by the continued widening of an individual crack as the fibers bridging that crack debond and pull out of the matrix. The same behavior has been observed by (Graybeal, B. and Baby, F., 2013). Table 5 Provide the test results of each set.

Table 5. Uniaxial tensile response results

Specimen Set	*First cracking strength (MPa)*	*Maximum cracking strength (MPa)*	*Strain at crack saturation*	*Strain at crack localization*
GP_ 28d	8.1	11.3	0.0012	0.0041
GP _91d	7.9	11.8	0.0015	0.0045
GP _HC	7	10.5	0.0013	0.0038
GP+GS_ 28d	7.6	11	0.0012	0.0044
GP+GS _91d	7.4	11.8	0.0013	-------
GP+GS _HC	6.8	12	0.0013	0.0041

Note: NC (normal curing); HC (hot curing)

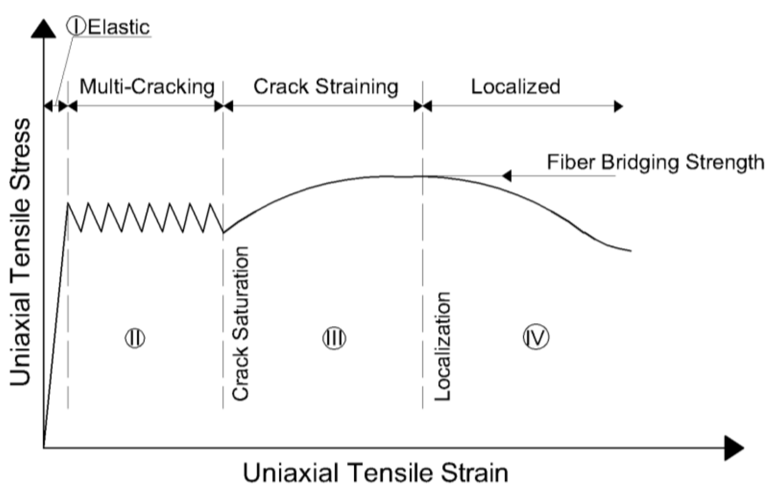


Figure 8. Idealized Uniaxial tensile response of UHPGC

CONCLUSIONS

Based the experimental and analytical results investigation presented herein, the following conclusions are presented:

1- Replacement with GP and GS have better flexural performance than replacement with GP only especially in terms of toughness and dissipated energy and this due to better rheological performance which lead to better dispersion of fiber.
2- The Double Edge Wedge Splitting (DEWS) is an indirect test which allows to provide the tensile stress versus the crack opening response of a cementitious composite without performing any back analysis.
3- From DEWS tests specimens with a favorable alignment of fibers (fibers perpendicular to the crack) reached the highest loads compared to those with an unfavorable fiber orientation.
4- From the comparison between different methods to identify the tensile properties of UHPGC, it has been observed that the tensile stress-strain response of UHPGC derived from flexural tests is slightly higher in terms of strength capacity when compared with curves obtained from DEWS tests.
5- In this program, the uniaxial stress – strain behavior of UHPGC in tension can be divided into four main phases: elastic phase, multi cracking phase, crack straining phase and localized phase.

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