Heliyon 9 (2023) e17926

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

# Mechanical and fracture characteristics of ultra-high performance concretes reinforced with hybridization of steel and glass fibers

Guler Fakhraddin Muhyaddin

*Construction and Materials Technology Department, Erbil Polytechnic University, Erbil, Iraq*

ARTICLE INFO

*Keywords:*
Characteristic length
Fracture energy
Glass fiber
Hooked-steel fiber
Micro-steel fiber
Toughness
Ultra-high performance concrete

ABSTRACT

Ultra-high performance concrete (UHPC) provides exceptional mechanical and durability properties, but it is highly prone to cracking. Despite short steel fibers have been introduced to UHPC mixtures to mitigate brittleness and improve ductility, its effect on the tensile strength and fracture toughness becomes rather limited. This experimental study addresses hybridization of micro steel and glass fibers, and long hooked steel fibers to improve mechanical and fracture properties of ultra-high-performance concretes (UHPCs). Totally, 22 concrete mixtures were cast using mono and binary combinations of micro steel fiber (MSF), long hooked steel fiber (HSF) and micro glass fiber (GF) at 0, 0.25, 0.50, 0.75, 1.0, 1.5, and 2% by total fiber volume. The UHPCs were tested for compression, splitting, flexure, load-deflection diagram, fracture toughness, and characteristic length. Combined use of fibers suggested the performance order of MSF + HSF, MSF + GF, and HSF + GF on the effects tested. Using hooked steel fibers (HSF) in the hybrid blends seems remarkably promising as it has provided much higher ductility and discernible strain hardening. Using mono-GF did not improve ductility, even showed brittle failure.

## 1. Introduction

Advances in concrete technology have increased the trend to develop the novel materials of construction with remarkably high strength and durability as the supplementary cementitious materials (SCMs), new generation superplasticizers (SPs), and high strength steel fibers have been brought to market. Ultrahigh-performance concrete was manufactured with its exceptional properties to minimize cracking and to prolong the service life of concrete structures in the late 1990s [1–3]. A very dense cementitious matrix associated with a discontinuous pore structure generates superior compressive and flexural strengths over 150 and 15 MPa, respectively [4–7]. However, the combination of ultrahigh strength, brittleness, and homogeneity makes UHPC highly prone to cracking; thus, the use of fibers to reinforce plain UHPCs becomes inevitable and the material is called UHPFRC hereafter.

UHPFRC has a longer service life with improved cracking resistance and high strength under tension owing to the linking of fibers across the cracks [8,9]. The most important parameters of the fibers to produce high mechanical anchorage are stiffness, fiber strength, and bonding ability with concrete. Bonding of the fiber with concrete is mainly affected by aspect ratio, shape and surface texture. Hooked fibers usually have an aspect ratio and length greater than 80 and 30 mm, respectively, yielding better mechanical concrete properties than microfibers [9–11]. Moreover, the compressive strength and flexural toughness associated with the post-peak behavior of UHPFRC are enhanced by incorporating microfibers [6,12,13]. Opposed to the mechanical properties, fibers in UHPCs can remarkably worsen the workability since the total surface area to be wetted by the mixing water increases so that free water content

*E-mail address:* guler.muhyaddin@epu.edu.iq.

https://doi.org/10.1016/j.heliyon.2023.e17926
Received 21 January 2023; Received in revised form 6 May 2023; Accepted 1 July 2023
Available online 4 July 2023

needed to lubricate cement particles decreases [14]. To overcome the workability loss, high-power mixers working with much more energy are employed to mix the fresh concrete reinforced with either long-deformed fibers or fibers of high volume [15,16]. Compromise in the workability of UHPC can weaken the hardened properties and/or rise the cost. Therefore, producing cost-effective and workable UHPC necessitates a low amount of fiber that can be accomplished by the hybrid use [9,15,16].

Concept of a hybrid fiber reinforced cementitious composite (HFRCC) was initially introduced by Rossi [8]. Subsequently, Wille et al. [17] managed to produce UHPFRC with 200 MPa compressive strength and 15 MPa tensile strength as well as a strain capacity of 0.61%. Kim et al. [18] conducted a comparative study on the flexural behavior of fiber-reinforced cementitious composites. Out of the four fiber types used, the samples with steel twisted fibers yielded the best performance while the PVA-fiber specimens had the lowest efficiency. In another study by Kim et al. [19], four types of macrofibers accompanied by a smooth microsteel fiber were used to examine the modulus of rupture to optimize the fiber blend. Yoo et al. [20] reported that hybrid use of long and medium-length fibers enhanced the flexural strength, whereas long and short fibers in dual use decreased this concrete response. In the study of Niu et al. [21], crack propagations of UHPCs made with 2% fiber volume were investigated for flexure. The best properties were obtained in the mixture composed of medium length and long fibers. Dawood and Ramli [22] pointed out that increasing the hybrid fiber content produced greater strengths at both the first and the postcracks when palm and synthetic fibers were used together at 2%. Chun and You [23] studied the influence of macro- and micro steel fibers in the hybrid form. Test results proposed a lower ratio of fiber efficiency as the microfibers had replaced the macrofibers when the hooked and twisted fiber cases were considered. Reinforcement effect of steel fibers was investigated by Mpalascas et al. [24] using acustic emission (AE). At low load levels, acoustic emission behavior seemed to very indicative of the amount of reinforcement as well as of the ultimate mechanical properties. Kytinou et al. [25] investigated effects of steel fibers on the short-term behavior of realistic beams containing reinforcing bars and stirrups. Findings of the study revealed the favorable influence of steel fibers on the flexural behavior, the cracking performance, and the post-cracking residual stress. Similarly, Kachouh et al. [26] monitored the shear response of reinforced concrete (RC) deep beams including steel fibers. The addition of steel fibers remarkably improved the shear response of the tested RC-beams in the range of 30–80%. In the study of Hakeem et al. [27] effects of nano-silica and micro steel fiber on the properties of ultra-high performance concrete (UHPC) were explored. Despite the effect of micro-steel fiber on the compressive strength was inconclusive, its potential to improve tensile strength and modulus of elasticity was reported to be quite favorable. Glass fiber is generally used in certain types of UHPCs so that a little focus has been devoted to glass fiber reinforcement which may improve the tensile strength and ductility [28]. Yan et al. [29] studied possible improvement of the ductility characteristics of UHPFRCs incorporated with synthetic fibers such as basalt fiber, polypropylene fiber and glass fiber (GF) all of which being used in the single form. GF was found to enhance modulus of rupture and toughness.

## 2. Research significance

Ultra-high performance concrete (UHPC) provides exceptional mechanical and durability properties, but it is highly prone to cracking. Short steel fibers have been used in UHPC mixtures to benefit from its potential to improve tensile strength and modulus of elasticity while its effect on the compressive strength being inconclusive. Moreover, micro-steel fibers have rather limited effect on the tensile strength and fracture toughness despite long steel fibers can make UHPC highly resistant to cracking. Glass fiber is generally used in certain types of UHPCs, thus a little focus has been devoted to glass fiber reinforcement. However, combined use of fibers with varying properties seems necessary to provide ultra-high strength associated with enhanced ductility. This study has suggested to achieve UHPCs with such properties by using hybrid blends of micro steel and glass fibers, and hooked steel fibers.

## 3. Experimental study

### 3.1. UHPC mixture compositions

Cementitious materials used in mixture composition of UHPCs were CEM I 42.5R Portland cement conforming TS EN 197 [30] and Silica fume (SF) having specific gravity of 3.15 and 2.2, respectively, and specific surface area of 394 and 21,080 kg/m$^3$, respectively. Quartz aggregate of 2.65 specific gravity was incorporated in three fractions of 0–0.4, 0.6–1.2, and 1.2–2.5 mm. Plain UHPC was designed at a water-binder ratio of 0.195 and a cement-silica fume blend of 1200 kg/m$^3$. To reinforce the UHPCs, three types of fibers, namely Micro steel fiber (MSF), Hooked steel fiber (HSF), and Glass fiber (GF) were incorporated at 0.25%, 0.5%, 0.75%, 1%, 1.50% and 2% by volume. Table 1 presents physical and geometrical properties, and Fig. 1 shows a photographic view of the fibers used. 22 plain and fiber reinforced UHPC mixtures consisting of four subgroups were designed as seen in Table 2. Workability was ensured by a target slump flow of 23 $\pm$ 2 cm which being accomplished by using a new generation polycarboxilate based superplasticizer (SP) as per ASTM C 494 [31].

**Table 1**
Physical and geometrical properties of fibers.

| Types of Fiber | $d_f$ (mm) | $l_f$ (mm) | Aspect ratio ($l_f/d_f$) | Tensile Strength (MPa) | Elastic Modulus (GPa) |
|---|---|---|---|---|---|
| Micro fiber | 0.20 | 13 | 65.0 | 2500 | 200 |
| Hooked fiber | 0.75 | 60 | 80.0 | 1050 | 200 |
| Glass fiber | 0.025 | 6.35 | 1.0 | 1700 | 72 |

*Note*: $d_f$ = diameter of fiber and $l_f$ = length of fiber.

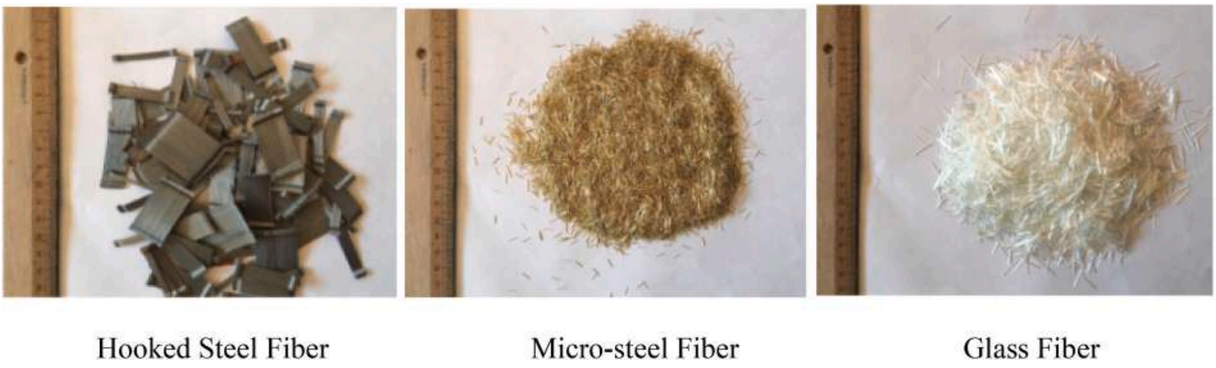


**Fig. 1.** Types of fibers used in this study.

**Table 2**
UHPC mixture proportioning, kg/m$^3$.

| Group | Mixture ID | Portland cement | Silica fume | Water | SP | Steel Micro Fiber | Hooked Steel Fiber | Glass Fiber | Aggregates |
|---|---|---|---|---|---|---|---|---|---|
| (1) Ref. Mixes | Control Plain | 960 | 240 | 234 | 45 | 0 | 0 | 0 | 793.7 |
| | MSF1.0 | 960 | 240 | 234 | 45 | 71.70 | 0 | 0 | 767.2 |
| | HSF1.0 | 960 | 240 | 234 | 45 | 0 | 78.5 | 0 | 764.7 |
| | GF1.0 | 960 | 240 | 234 | 45 | 0 | 0 | 26.0 | 798.8 |
| (2) (50% MSF+ 50% HSF) | MSFHSF0.25 | 960 | 240 | 234 | 57 | 8.96 | 9.81 | 0 | 757.6 |
| | MSFHSF0.50 | 960 | 240 | 234 | 45 | 17.93 | 19.63 | 0 | 780.5 |
| | MSFHSF0.75 | 960 | 240 | 234 | 45 | 26.89 | 29.44 | 0 | 773.8 |
| | MSFHSF1.00 | 960 | 240 | 234 | 45 | 35.85 | 39.25 | 0 | 767.2 |
| | MSFHSF1.50 | 960 | 240 | 234 | 45 | 53.78 | 58.88 | 0 | 754.0 |
| | MSFHSF2.00 | 960 | 240 | 234 | 51 | 71.70 | 78.50 | 0 | 726,0 |
| (3) (50% MSF + 50% GF) | MSFGF0.25 | 960 | 240 | 234 | 36 | 8.96 | 0 | 3.25 | 809,2 |
| | MSFGF0.50 | 960 | 240 | 234 | 36 | 17.93 | 0 | 6.50 | 802.5 |
| | MSFGF0.75 | 960 | 240 | 234 | 36 | 26.89 | 0 | 9.75 | 795.9 |
| | MSFGF1.00 | 960 | 240 | 234 | 36 | 35.85 | 0 | 13.00 | 789.3 |
| | MSFGF1.50 | 960 | 240 | 234 | 60 | 53.78 | 0 | 19.50 | 717.2 |
| | MSFGF2.00 | 960 | 240 | 234 | 63 | 71.70 | 0 | 26.00 | 696.5 |
| (4) (50% HSF + 50% GF) | HSFGF0.25 | 960 | 240 | 234 | 42 | 0 | 9.81 | 3.25 | 794.4 |
| | HSFGF0.50 | 960 | 240 | 234 | 42 | 0 | 19.63 | 6.50 | 787.8 |
| | HSFGF0.75 | 960 | 240 | 234 | 45 | 0 | 29.44 | 9.75 | 773.8 |
| | HSFGF1.00 | 960 | 240 | 234 | 45 | 0 | 39.25 | 13.00 | 767.2 |
| | HSFGF1.50 | 960 | 240 | 234 | 51 | 0 | 58.88 | 19.50 | 739.2 |
| | HSFGF2.00 | 960 | 240 | 234 | 57 | 0 | 78.50 | 26.00 | 711.3 |

UHPCs with none and 1% fiber content are fixed to those in Ref. [6] because the same materials have been used in concrete manufacturing. Therefore, the concretes within the first group in Table 2 designate the reference concretes, namely plain UHPC with no fiber as well as UHPCs containing 1% volume of micro steel fiber (MSF1.0), Hooked steel fiber (HSF1.0), and Glass fiber (GF1.0). However, the concretes in the second group in Table 2 were produced with MSF and HSF each of which constituted half of the total fiber volume in the mixture. Hence, MSF + HSF 1.0 indicates the UHPC with 0.5% of micro-steel fiber and 0.5% of hooked steel fiber by volume. The third and fourth groups of concretes were replication of the second group in such a way that MSF and GF, and HSF and GF were used in the former and in the latter, respectively.

Mixing sequence of the HPFRC was adopted from the previous studies [6,15,16]. Firstly, dry aggregates were mixed in a Hobart mixer for 3 min at relatively low speed of 100 rpm. Next, half of the water was incorporated to the aggregates which being remixed at the same speed for 5 min. Then, the superplasticizer and remaining water were introduced into the premixed mixture, and the mixing was resumed at a high speed of 470 rpm for 5 min. Finally, fresh concrete was cast into the steel molds and compacted using a vibrating table. Thereafter, the samples were covered by polyethylene sheets and kept at 22 °C for 16 h. Subsequently, samples were cured in water till the testing age.

### *3.2. Testing methods*

Three 50 mm cubes were tested for compression at 28 and 90 days, respectively after casting as recommended by ASTM C39 [32]. Splitting tensile strength was measured on three 100 m cubes at 90 days according to ASTM C496 [33]. Static elastic modulus was measured on three 150 cubes at 90 days as per ASTM C469 [34]. For each test category, the results presented herein were the average of three samples.

As suggested by Technical Committee of RILEM 50-FMC/198 [35] and Ref. [6], fracture properties of the concretes were determined on notched beams by means of a close-loop 250 kN Instron machine as seen in Fig. 2. The displacement at mid-span was measured via two linear variable displacement transducers (LVDTs) fixed on two sides of concrete beams. The test was carried out on the pre-notched beams at a constant pace rate of 0.02 mm/min. Before the test, a 28 mm deep notch was cut by means of a concrete sawing machine so that the cross-section was decreased to 42 by 70 mm so a notch to depth ratio of 0.4 being provided. Two beams were tested for each mixture at 90 days. Fracture energy ($G_F$), flexural strength ($f_{flex}$), and characteristic length ($l_{ch}$) were computed by the equations below:

$$G_F = \frac{W_o + mg\delta_s \frac{S}{U}}{B(W-a)} \tag{1}$$

$$f_{flex} = \frac{3P_{max}S}{2B(W-a)^2} \tag{2}$$

$$l_{ch} = \frac{EG_F}{f_{st}^{\ 2}} \tag{3}$$

where, $W_0$: the area underneath the load–deflection curve; m: mass of the concrete beam; g: gravitational acceleration; $\delta_s$: target displacement; S: span; U: length of beam; B: width of beam; W: depth of beam; a: notch depth; $P_{max}$: peak load on the load-deflection diagram; E: static modulus of elasticity; $f_{st}$: splitting tensile strength.

## 4. Results and discussions

### 4.1. Compressive strength

Compressive strength of the nonfibrous UHPC, and mono and dual fiber reinforced UHPCs are presented in Fig. 3. It was observed that incorporating hybrid fibers in the mixtures considerably increased the compressive strength of UHPC. The strength increase was nearly monotonic up to 2% fiber volume. Compressive strengths of the nonfibrous control concrete at 28 and 90 days were 136.0 MPa and 156.0 MPa, respectively. With the combined use of fibers, however, compressive strength substantially increased. Indeed, the mixture MSF + HSF showed the highest 90-day compressive strength of 183 MPa, followed by MSF + MGF mixture with 178 MPa as well as HSF + MGF mixture with of 172 MPa at a fiber volume of 2%. This can be referred to the similar working mechanisms of the hybrid fibers across the micro and macro cracks. Homogeneity and consistency provided by the compatible intrinsic properties of the fibers may have played an important role which brought about the performance order of MSF + HSF, MSF + MGF, and HSF + MGF. Irrespective of the fiber length, steel to steel conformity of the hooked end and micro-steel fibers had superior compatibility which in turn led to more homogenous matrix under compression. On the other hand, regardless to the fiber type, higher strength of MSF + MGF mixture than that of HSF + MGF is probably based on the consistency of short-to-short fibers in the former rather than long to short fibers in the later.

Fig. 4 shows the comparison of UHPCs made with mono and hybrid fibers. It was seen that the concretes containing 1% mono-MSF

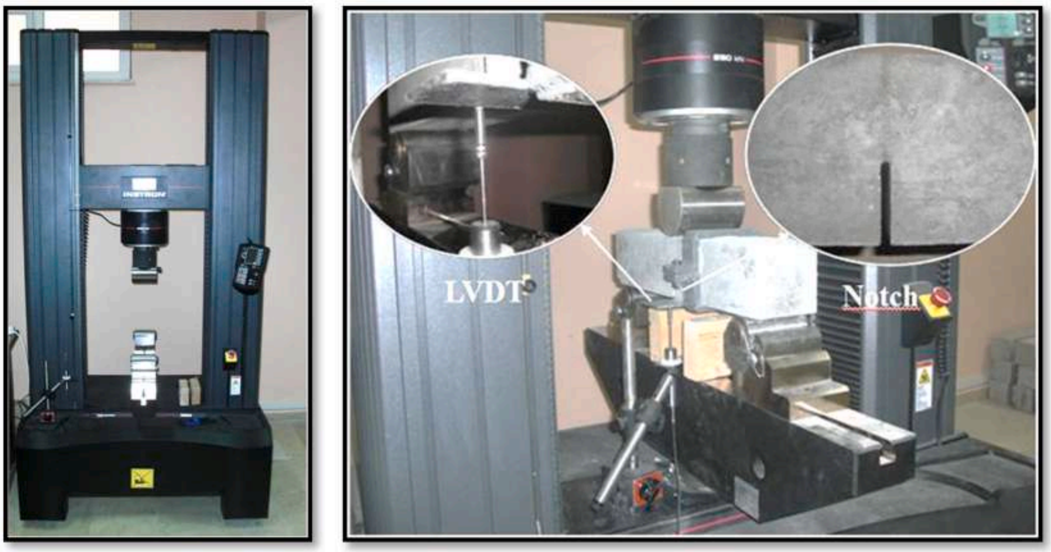


**Fig. 2.** Three point bending testing machine and test specimen.

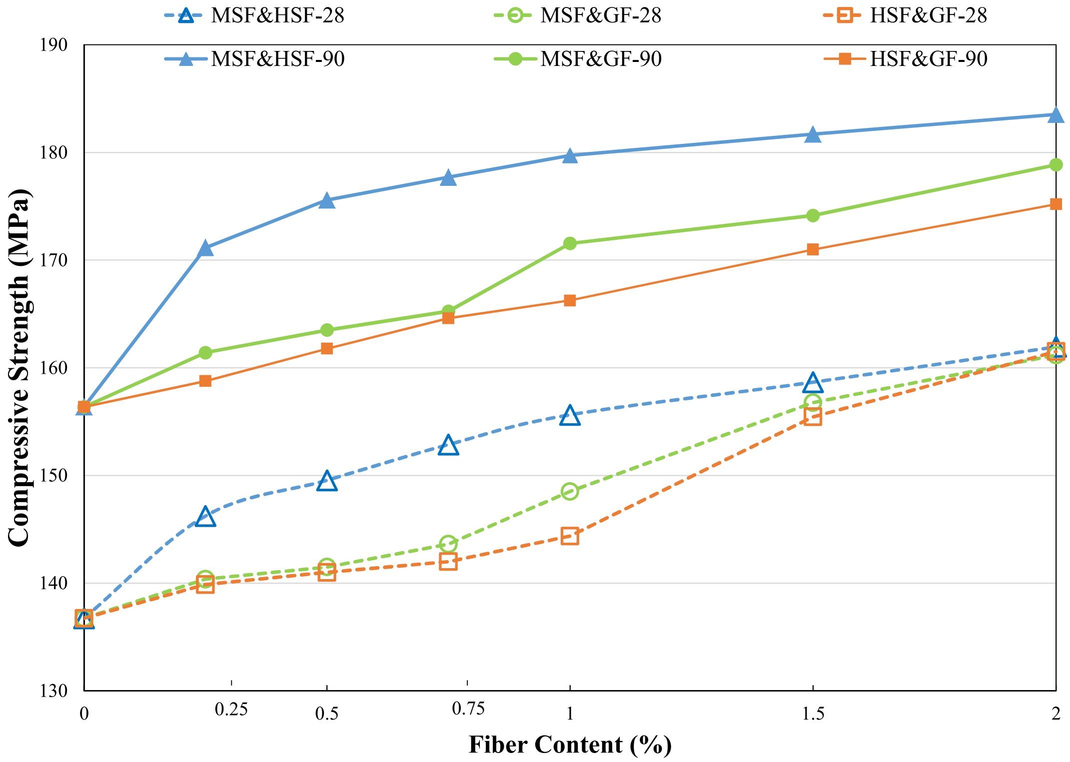


**Fig. 3.** Compressive strength of the concrete mixtures with combined fibers.

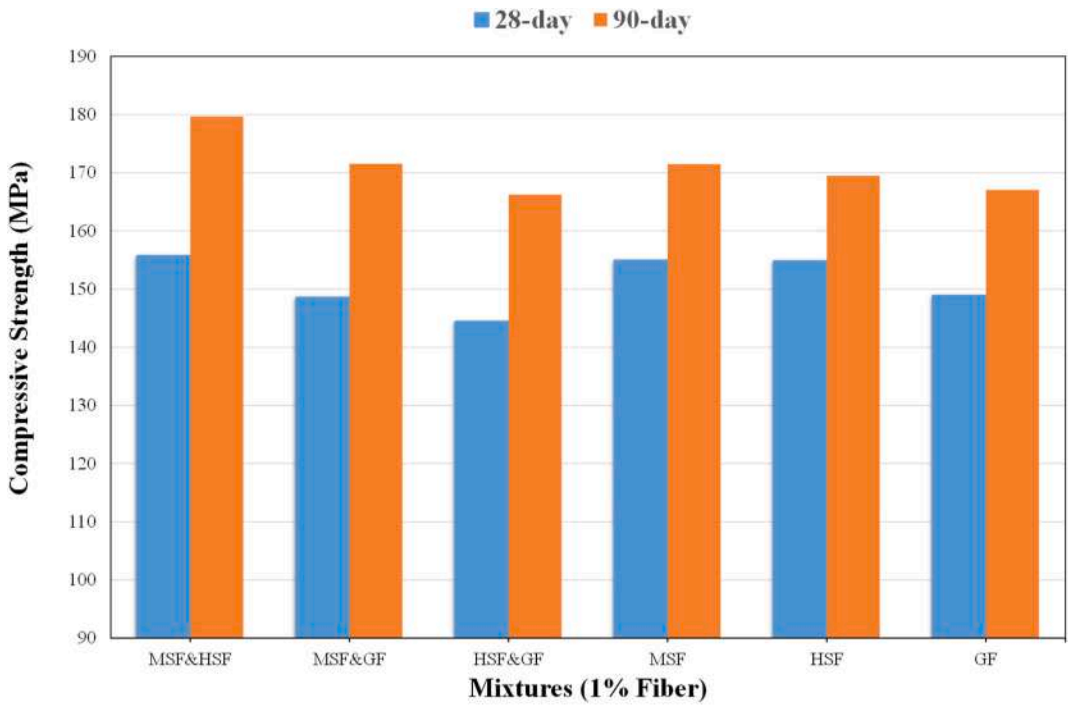


**Fig. 4.** Effect of combined use of fibers on the compressive strength of UHPCs at 1% fiber volume.

and mono-HSF had 90-day compressive strengths of 171 and 169 MPa, respectively while that of MSF + HSF mixture was 179 MPa. Therefore, hybrid use of MSF and HSF provided a further strength increase by about 6%. It was also noticed in Fig. 4 that the MSF + HSF and HSF + GF combinations gave the highest and the lowest compressive strengths, respectively. Rate of influence on the compressive strength followed the order of MSF, GF, and HSF. Overall, using HSF decreased the compressive strength due to high amount of SP used to maintain the target slump flow which in turn increased the volume of entrapped air and lowered the compressive strength. Moreover, using long fibers in the mixtures caused agglomeration of the fibers which was handled by increasing the amount of SP and mixing energy. Thus, it was rather hard in some cases to have uniformly distributed fibers which again decreased the compressive strength.

### 4.2. Splitting tensile strength

Fig. 5 shows splitting tensile strength of the concretes with mono-fibers and fiber blends of MSF + HSF, MSF + GF, and HSF + GF. The behavior in splitting test was similar to that seen in the compression. With increasing the fiber content up to 2%, the concretes had higher splitting tensile strengths. The control plain concrete had a splitting tensile strength of 8.4 MPa which raised to 10.42, 9.67, and 9.58 MPa when 2% of MSF + HSF, MSF + GF, and HSF + GF were introduced to the mixtures, respectively. Fiber size also appeared to influence the splitting tensile strength such that the mixtures with micro steel fibers had greater tensile strengths than the mixtures containing hooked steel fibers. Therefore, regarding the splitting tensile strength, the order of performance was found to be MSF + GF, MSF + HSF, and HSF + GF, respectively. Such results were 30, 22, and 16% greater than the control concrete, respectively. Similarly, 1% of fiber reinforcement added up the tensile strength with a lower rate in comparison to 2%. Indeed, the concretes with 1% hybrid fibers provided strength improvements by about 22, 17, and 9%, respectively. However, when the 1% of mono fiber was used in the reinforcement of plain UHPC, the MSF, HSF, and GF reinforced concretes had about 15%, 11%, and 7% greater strengths in comparison to the plain concrete. Thus, combined use of GF and HSF had adverse effect on the splitting tensile strength because of the weaker bond between concrete and the glass fiber. Also, using hooked end steel fiber in presence of the glass fiber increased the SP demand to keep the desired workability, which again diminished the tensile strength. It was detected in Fig. 6 that the concretes made with MSF and/or HSF did not split apart. In addition to bridging effects of the fibers, a good matrix-fiber bond between concrete and steel accounted for this behavior [36,37]. Yu et al. [38] explained that short steel fibers could tolerate the microcracks more efficiently than long steel fibers for a given fiber content because they were very thin and their number in concrete being much higher than the latter.

### 4.3. Modulus of elasticity

Fig. 7 demonstrates static elastic moduli of the concretes with the hybrid fibers of different types and contents. It was recognized

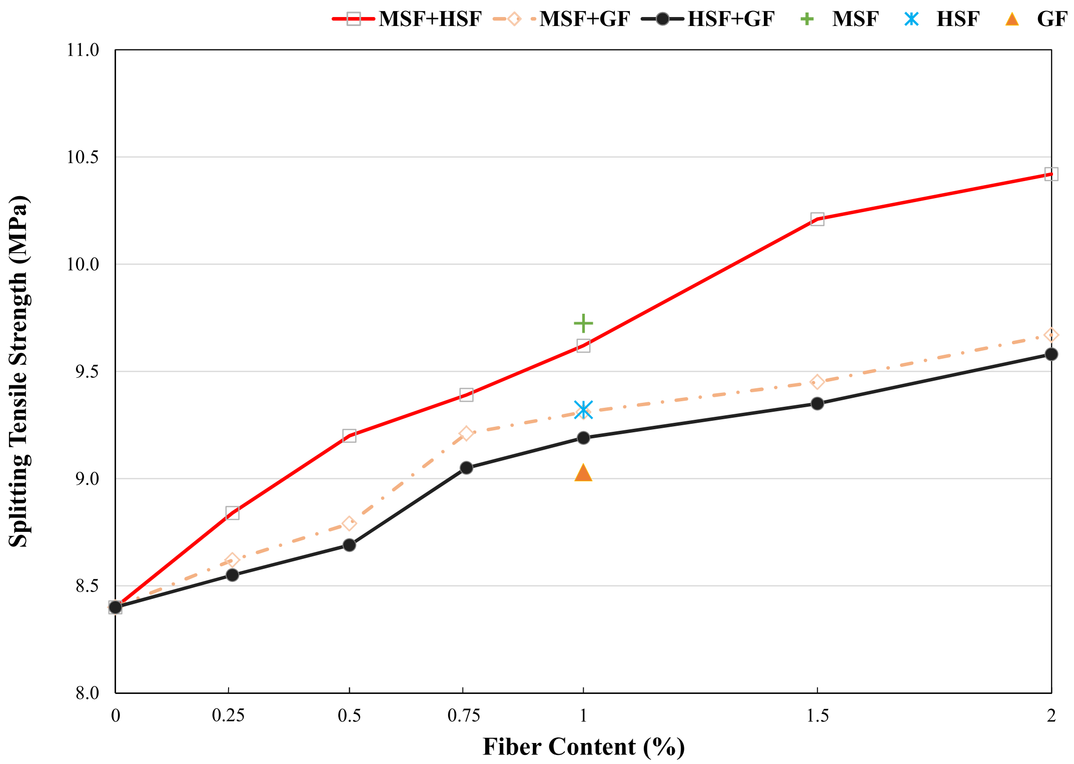


**Fig. 5.** Effect of combined use of fibers on the splitting tensile strength of UHPCs.

**Fig. 6.** View of UHPC containing both MSF and HSF.

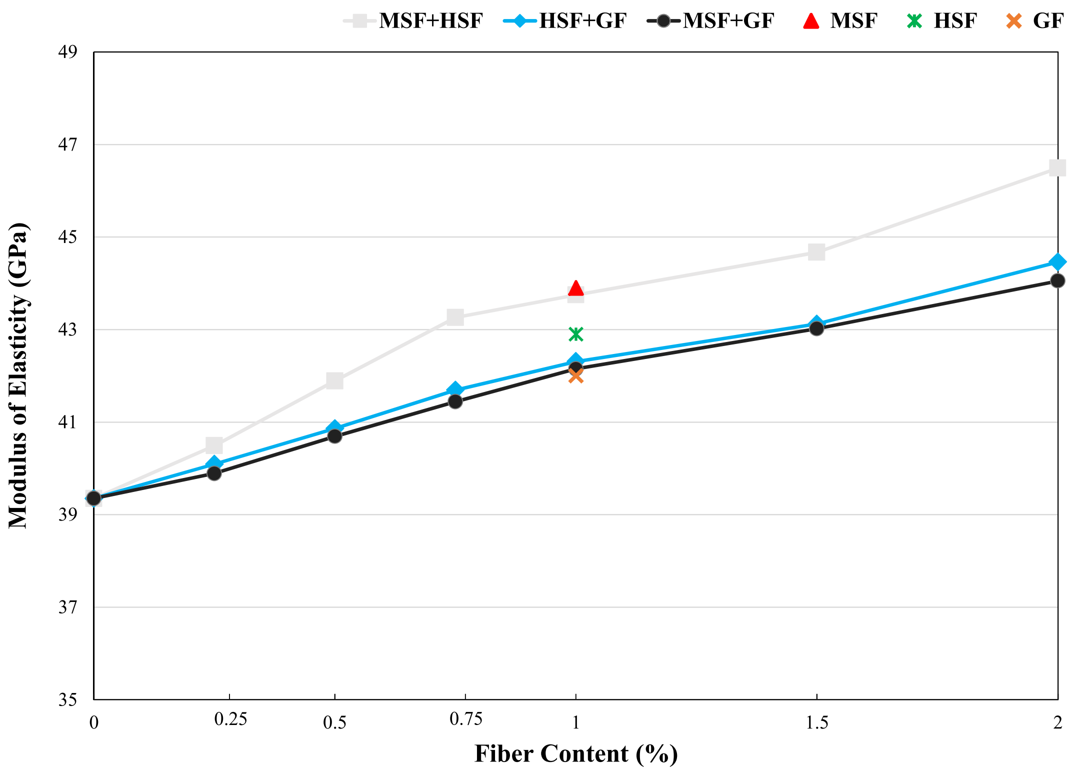


**Fig. 7.** Effect of combined use of fibers on the elastic moduli of UHPCs.

that adding 0.25, 0.5, 0.75, 1, 1.5 and 2% of MSF + HSF and MSF + GF enhanced the elastic modulus by 3.97, 6.92, 12.06, 13.57, 15.97, and 16.79% in the case of former, and 3.97%, 6.92%, 12.06%, 13.57%, 15.97%, and 16.79% in the case of latter, respectively. However, using the same amount of HSF + MGF yielded increments of 1.79, 3.97, 6.35, 6.92, 9.92, and 8.65%, respectively, when compared to the reference mixture. Greater elastic moduli of the concretes reinforced with steel fibers (micro and hooked) results from orientation mechanism of the steel fibers. Because the density of steel fibers being much higher than that of the glass fiber, they have a greater orientation tendency causing to align in the stream direction.

As seen in Fig. 7 that combined use of MSF and HSF had no marked effect to improve the elastic moduli of the concretes made with mono MSF despite it helped to improve the elastic modulus of HSF reinforced concrete by as low as 2%. Fig. 7 also revealed that using GF in any combination negatively affected the elastic moduli of the concretes with respect to those made only with MSF or HSF.

### 4.4. Flexural strength

Flexural strengths of the plain UHPC and UHPRCs are displayed in Fig. 8. It was seen that higher the fiber content, the concretes had higher flexural strengths inasmuch as more fibers enhanced the capability of delaying the microcrack formation and arresting crack propagation. However, this strength improvement almost disappeared after 1% of fiber volume when the GF was incorporated in the mixtures. Similarly, the concretes with mono MSF had the lowest flexural strength. Lower strength of the concretes with either MSF or GF may result from the weak bond generated between the fiber and the concrete so that the fibers have failed to arrest the cracks. The weak bond of the former results from its inadequate length to create the necessary bond strength. The weak bond due to glassy surface of the latter helps ease of fiber-slippage. Unlike the behavior seen in compression and splitting, the effect of HSF was more favorable on the flexure due to the fact that bridging the cracks, and delaying the propagation by HSF were considerably superior so that it might transform the fracture behavior of concrete from brittle to ductile. Moreover, longer length and hook ends of the HSF provided a good bond between the fiber and the concrete which helped in having the best performance for flexure. Indeed, the concretes with HSF had significantly greater flexural strength regardless of its use in single or combined form. Seven MPa flexural strength of non-fibrous concrete increased to 13.4 MPa provided that the concrete included only 1% HSF, and to 15.23 and 14.74 MPa in the case of concretes with 1% of MSF + HSF and HSF + GF, respectively. Single use of HSF at 1% volume improved the flexural strength by 91%. Similarly, the combined use of HSF with MSF or GF improved the flexural strengths by 118 and 110%, respectively. Given a 1% fiber content, the combined use of fibers provided 27% and 19% further enhancement of the strength, respectively compared to that of single use of HSF. As a result of excellent crack prevention, macrocracks by the long fibers as well as microcracks by the short fibers, a marked rise in the flexural strength is observed after the hybrid fibers have been used [39–41].

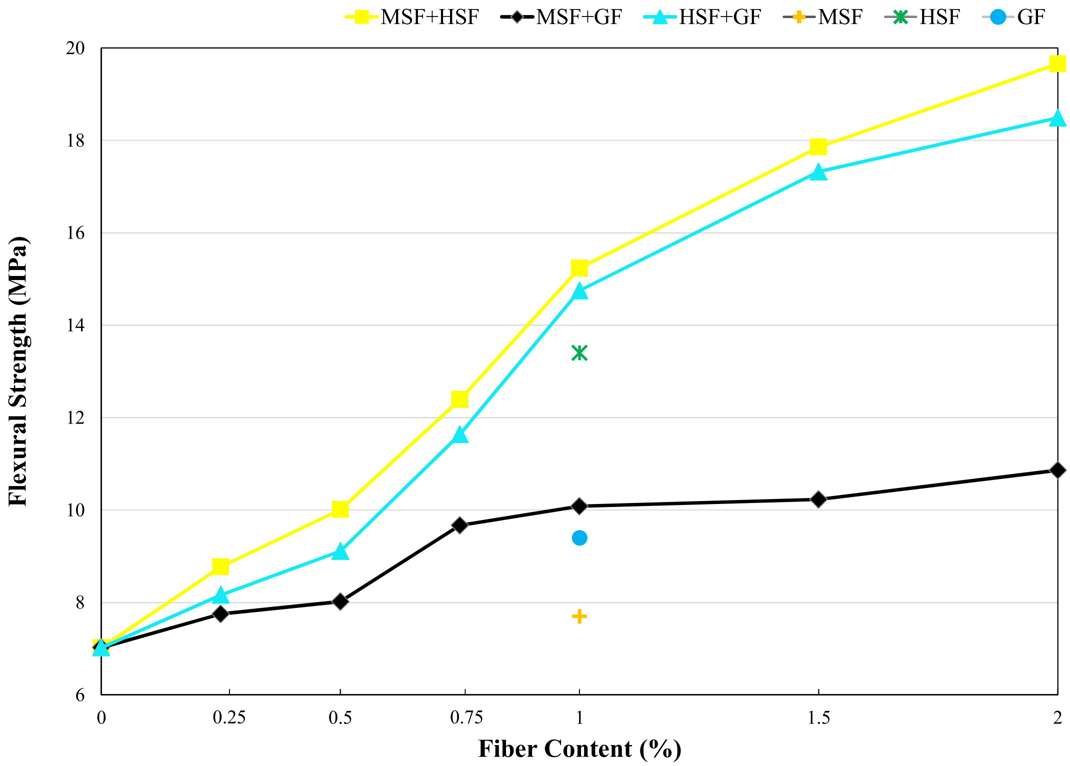


**Fig. 8.** Effect of combined use of fibers on the flexural strength of UHPCs.

### *4.5. Load–deflection diagrams*

Effect of using mono or hybrid reinforcing fibers of varying size, shape, and type are well presented in Figs. 9–12. It was observed in Fig. 9 that mono and hybrid use of MSF, HSF, and GF at a fiber volume of 0.5% are considerably effective on the prepeak-and post-peak behaviors. Load-deflection diagram of the non-fibrous concrete exhibited a well-defined brittle behavior such that the load almost linearly increased till the first crack load which being identical to the peak load. Thereafter, there was a very sharp fall to nearly zero load and the test ended up with a brittle failure. Likewise, the mixture made with mono GF showed a linear load-deflection behavior up to the peak load followed by a sudden drop with no residual load so that the failure type being nearly brittle. Even though MSF1.0 concrete demonstrated much similar behavior to that of GF concrete up to the peak load, the post-peak part of the load-deflection diagram slightly differed. Indeed, once the load had reached the peak, the sample suffered a sudden load reduction, but thereafter it continued to carry a residual load of 500 N with a curve tail of 1.8 mm, thus leading to ductile failure.

The HSF modified concretes, however, had significantly different load-deflection behaviors. Even the combined use of HSF and MSF at a total fiber volume of 0.5% remarkably altered the diagram to show a strain hardening behavior as seen in Figs. 9, 10 and 12. Interestingly, they displayed nonlinear increase until the first crack, and then the load slightly dropped at the low fiber content. When the total fiber volume was greater or equal to 0.75%, the load continuously increased without any loss to reach the peak load with small zig-zac pattern owing to the repeated fiber bridging, thus resulting in a strain hardening (Figs. 10 and 12). Following the peak, the load began to decrease gradually associated with a more detectable zig-zac pattern. The specimens did not undergo any marked decrease in the load even at this stage. The uneven descending branch had a fluctuating pattern caused by the progressive fiber bridging. Moreover, fiber pull-out in the residual load phase contributed to the much rougher zig-zac tail [6,42,43]. Residual load carrying capacity was much higher even at 4 mm deflection as seen in Figs. 10 and 12 (HSF + MSF and HSF + GF). Like mono-HSF, combined use of HSF and MSF or HSF and GF even at a total fiber volume of 0.5% caused the diagrams to display strain hardening as seen in Fig. 9. Different from only MSF or GF modified concretes, there was a small load drop at the first crack which began to increase by the fiber bridging. Addition of only 0.25% fiber volume of HSF almost doubled the residual load of concrete when compared to that with 0.5% MSF or GF.

As emphasized above fiber bridging helped in UHPFRC having outstanding tensile behavior in comparison to the non-fibrous concrete. Peak load on the load-deflection curve is remarkably affected by the type and content of the fiber used. Pre-peak and

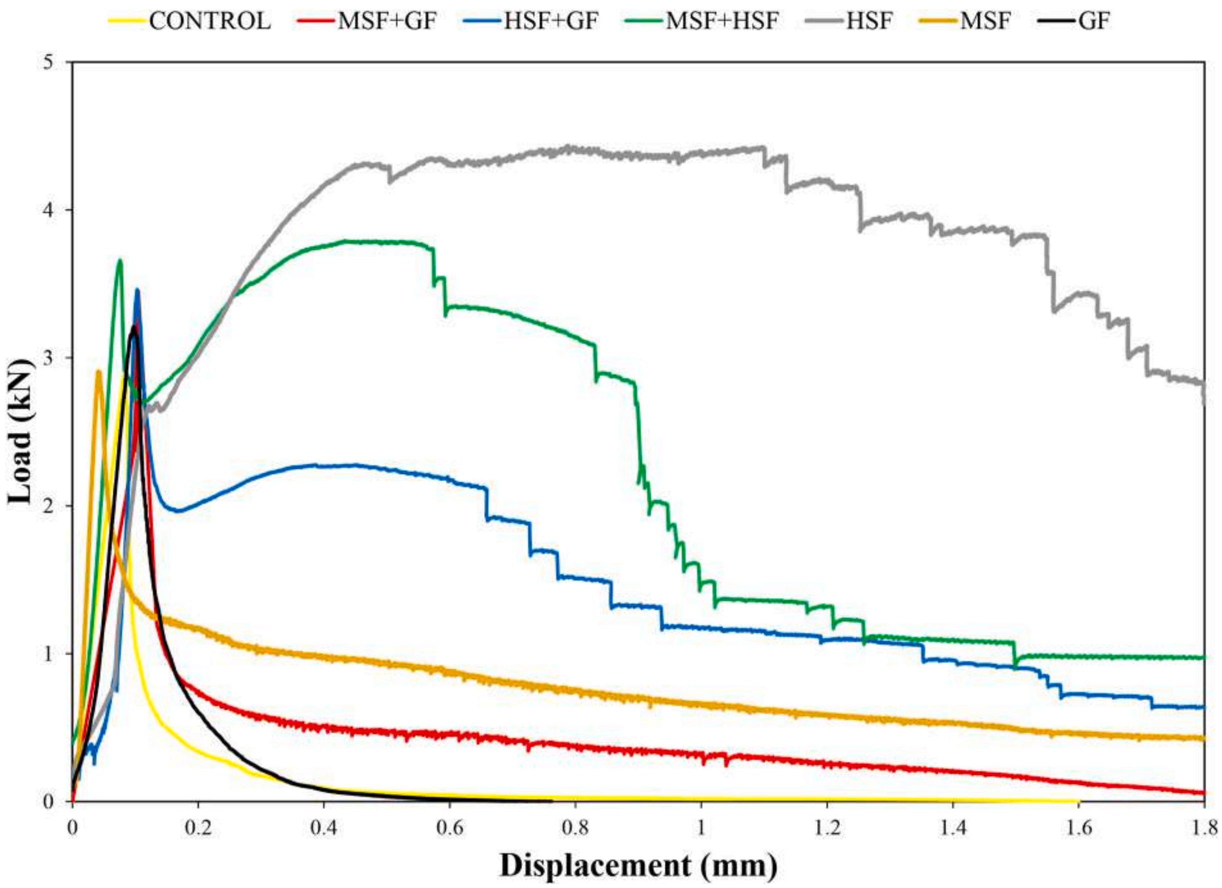


**Fig. 9.** Load-displacement behavior of UHPCs with 0.5% fiber content.

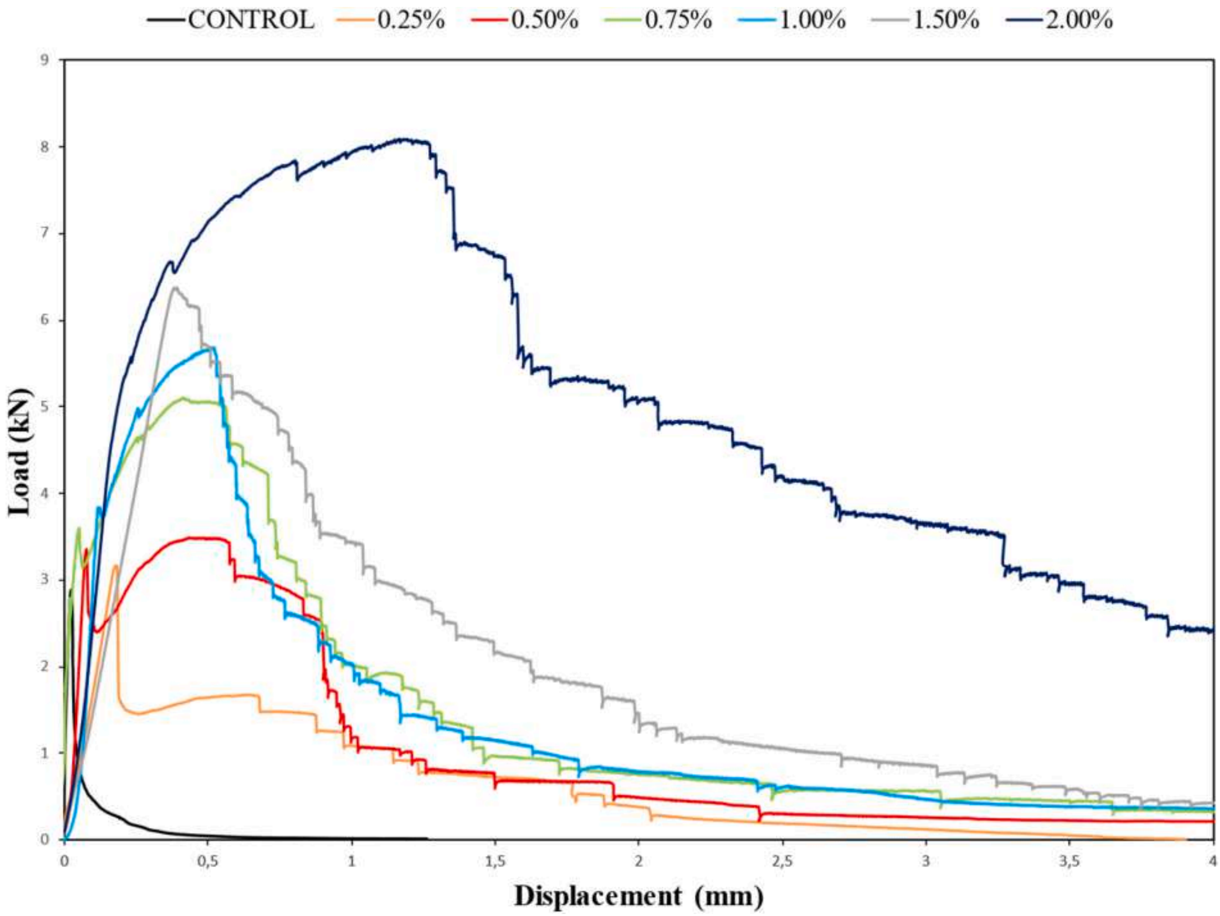


**Fig. 10.** Load-displacement behavior of UHPCs with MSF and HSF.

early post-peak regions of the curve were mostly related to the fiber content. Even though the structure becomes more ductile with increased fiber content in the case of conventional fiber reinforced concretes, the displacement measured at the peak load does not have a well observed tendency in UHPFRC. Yet, it combines the superior features of ultra-high performance and fiber reinforced concretes, strength of the former and ductility of the latter [44]. Voutetaki et al. reported similar results regarding effect of synthetic fibers [45]. Although the fiber reinforced concrete (FRC) exhibited a rather slight increase in the compressive strength with respect to plain concrete (PC), the most important influence of the synthetic fibers to the compressive behavior is the improvement of the post-peak response. The descending part in the stress-versus-strain diagram of FRC cube indicated the ability of the composite material to provide a rather ductile post-cracking response with respect to the brittle response of the PC cube. Deifalla et al. [46] attributes this behavior to fiber bridging. As soon as a crack begins to form, the fibers are activated. When a crack begins to widen, it comes into contact with a number of fibers that are either perpendicular to it or positioned at an angle and resist its widening. The gradual activation of the fibers transforms overall behavior of the concrete from brittle to ductile, enhances the energy dissipation capacity and reduces the width of cracks.

### *4.6. Fracture energy ($G_F$)*

A crack of a unit surface area generated by the total energy is defined as the Fracture energy ($G_F$). It $G_F$ is a function of the area underneath the load-deflection curve, weight of the concrete prism, and the displacement at which final failure occurs. Fig. 13 demonstrates the total fracture energy of UHPFRCs at 90 days. The highest fracture energy was achieved in the mixture of MSF + HSF. The reason for this is the longer softening part of the load-deflection curves of the concretes containing HSF even at very low fiber content. At 1% fiber volume, the fracture energy of the concretes containing mono MSF, GF, and HSF were 212, 805, and 4030 N/m, respectively. However, the concretes with MSF + HSF, MSF + GF, and HSF + GF had fracture energy of 4493, 1338, and 3690 N/m, respectively. In the presence of HSF, the fracture energy remarkably increased and surpassed those of the concretes with MSF and/or GF. The fracture energy enhanced with increasing the fiber content such that this effect being more favorable at higher fiber contents. Among the combinations examined, the lowest performance belonged to the MSF + GF reinforced concretes while MSF + HSF had the best, thus suggesting hybrid use of HSF and MSF as being more favorable. Indeed, very low amount of hooked end steel fibers improves

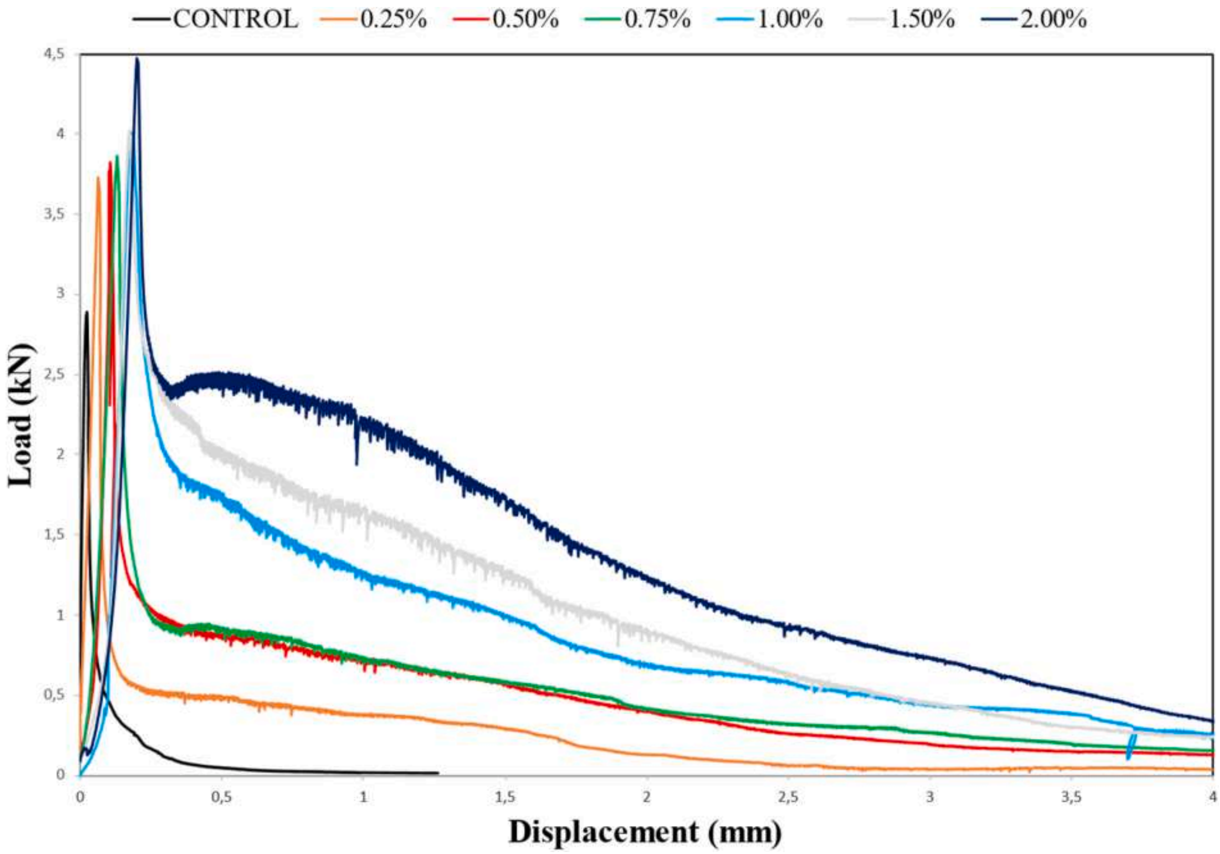


**Fig. 11.** Load-displacement behavior of UHPCs with MSF and GF.

the tensile strength of UHPC because mechanical anchorage of such fibers is created not only by bonding along the fiber but also by its hooked ends that penetrated the concrete matrix. Therefore, much higher resistance to tension load can be achieved. The micro straight fibers can favorably take multiple microcracking under control and add up the strain hardening [6,47].

### *4.7. Characteristic length*

As given in Eq. (3), characteristic length, $l_{ch}$ mainly depends on fracture energy, static modulus of elasticity, and splitting tensile strength. It accounts for the concrete ductility so that the concrete of higher characteristic length is said to be more ductile. The variation in $l_{ch}$ of the UHPFRCs with the fiber content and type are depicted in Fig. 14. Effect of fibers on the characteristic length was quite significant. For instance, characteristic length of the nonfibrous concrete was 44 mm while those of UHPFRCs almost ranged between 750 and 3000 mm. Then, using hybrid fibers greatly enhanced the characteristic length and made the concretes more ductile. At a 1% fiber volume, hybrid fiber combination seemed to be much more favorable than the single use. GF or MSF reinforced concretes had only 109- and 349-mm characteristic lengths, respectively. However, that of HSF reinforced concrete was as high as 1990 mm. By using the MSF or GF in the presence of HSF, such concretes displayed remarkable characteristic lengths of 2124 and 1841 mm, respectively. Therefore, HSF added concretes seemed to be more ductile in line with the load-deflection behavior, fracture energy, and flexural strength. Moreover, effect of the fiber content was more detectable for the concretes with HSF. Then, the concretes with MSF + HSF or MSF + GF offered more ductile behavior in comparison to those with MSF + GF.

## 5. Conclusions

Considering the outcomes of this experimental research, the following conclusions are drawn:

1. Compressive strength of the concretes with hybrid fibers ranged within a narrow band, the highest of 183 MPa and the lowest of 172 MPa were achieved for MSF + HSF and HSF + GF combinations, respectively. Given a fiber volume of 1%, combined use of MSF + HSF gave a 6% further strength increase compared to the mono use of MSF or HSF. However, HSF + GF fiber combination appeared to have slightly negative effect while that of MSF + GF was almost negligible.

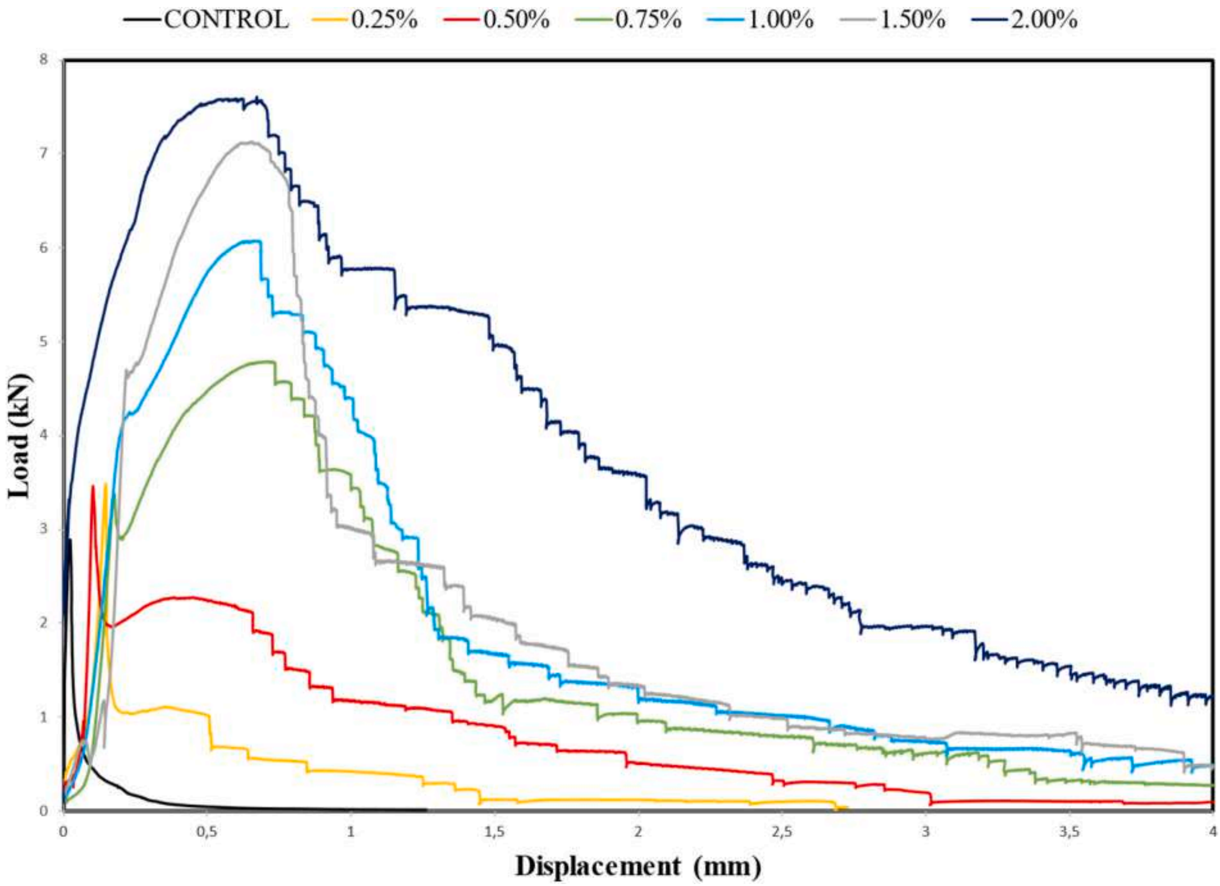


**Fig. 12.** Load-displacement behavior of UHPCs with HSF and GF.

2. Based on the plain reference concrete, tensile strengths of the fiber reinforced concretes were greater by 30, 22, and 16% in the order of MSF + GF, MSF + HSF, and HSF + GF, respectively. Incorporating mono fibers of MSF, GF, and HSF at 1% provided strength increase of 15%, 11%, and 7%, respectively. Combined use of GF and HSF had adverse effect on the splitting-tensile strength due to the weaker bond between the concrete and the glass fiber.
3. There was no marked difference between the elastic moduli of the concretes made with mono MSF and hybrid MSF + HSF. Moreover, presence of GF in any combination negatively affected the elastic moduli of the concretes.
4. The best fiber performance was observed on the specimens tested for flexure. This behavior is attributed to increase of the fiber ability to delay the micro-crack formation and to arrest crack propagation. Flexural strength of the concretes was found to be lower when the short fibers, MSF or GF, had been used. However, the concretes with HSF had significantly greater flexural strength regardless of its use in single or combined form. Single use of HSF at 1% improved the flexural strength by 91%. When the HSF was used together with MSF or GF, further improvements of 27% and 19%, respectively were achieved.
5. Like non-fibrous concrete, the concretes made with only GF showed a linear load-deflection relationship, thereafter it ended up with a brittle failure of no residual load. The concrete with mono MSF demonstrated much similar behavior to that of GF-concrete up to the peak load. In the post-peak stage, however, such concrete was able to carry residual load ending with a more ductile failure.
6. Incorporating mono or hybrid HSF in the mixtures led the load-deflection diagrams to show strain hardening with a considerably longer descending branch, even at 0.5% fiber volume. Although the peak load did not exceed that of the first crack at low fiber content, the softening descending branch was much longer associated with much greater residual load carrying capacity. Especially, after a total fiber content of 0.75%, load continuously increased resulting in a well observed strain hardening. Addition of only 0.25% fiber volume of HSF almost doubled the sustaining load of concrete when compared to that with 0.5% MSF or GF.
7. The highest fracture energy was achieved in the mixture of MSF + HSF. This is attributed to the large descending branch of the load-deflection curves of the concretes. At a 1% fiber volume, the fracture energy of the concretes containing mono MSF, GF, and HSF were 212, 805, and 4030 N/m, respectively. However, the concretes with MSF + HSF, MSF + GF, and HSF + GF had fracture energy of 4493, 1338, and 3690 N/m, respectively. As soon as the concretes contained HSF, the fracture energy remarkably increased and surpassed those of the concretes without it.

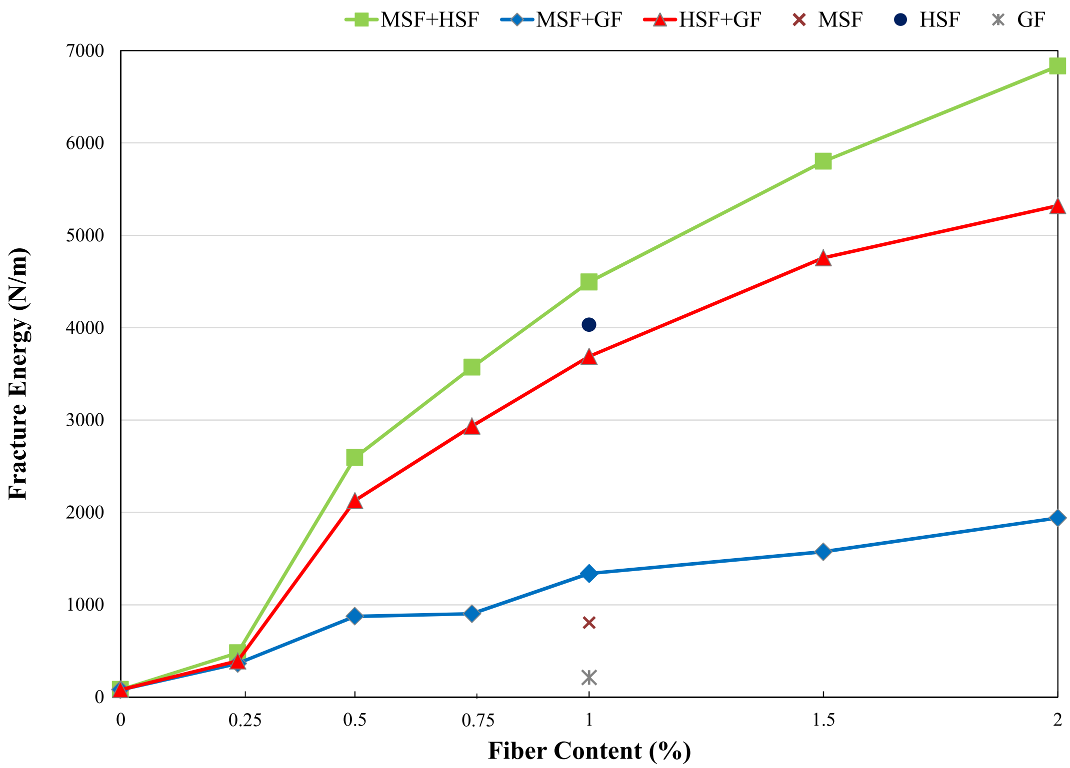


**Fig. 13.** Effect of combined use of fibers on the fracture energy of UHPCs.

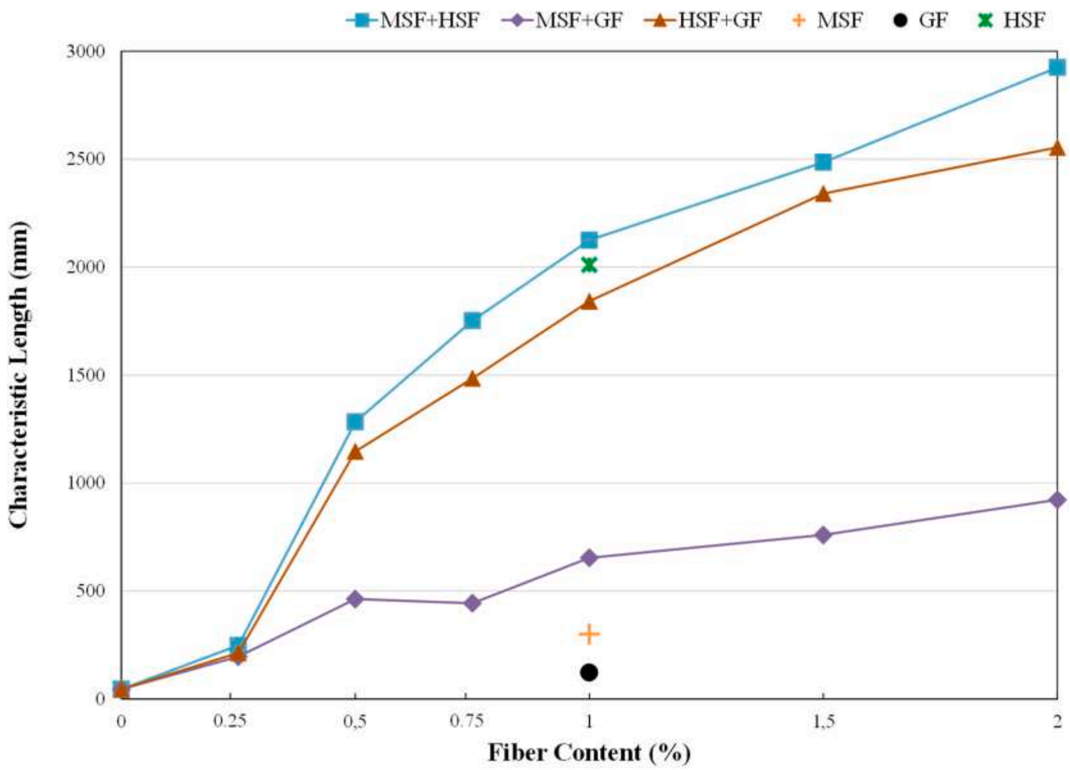


**Fig. 14.** Effect of combined use of fibers on the characteristic length of UHPCs.

8. The characteristic length seemed to be significant on the brittleness of such concretes as the characteristic length was almost ranging between 750 and 3000 mm as that of the nonfibrous concrete being 44 mm. Combined use of the fibers greatly enhanced the characteristic length which increased with the fiber content. GF or MSF reinforced concretes had only 109- and 349-mm characteristic lengths, respectively. By using the MSF or GF in the presence of HSF, they also displayed remarkable characteristic length of 2124 and 1841 mm, respectively. HSF added concretes seemed to be more ductile in line with the load-deflection behavior, fracture energy, and flexural strength.

## Author contribution statement

Guler muhyaddin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

## Data availability statement

No data was used for the research described in the article.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## References

[1] C.A. Richter, Properties and Behavior of UHPC-Class Materials, Technical report, Turner-Fairbank Highway Research Center, McLean, VA, 2018.
[2] G.D. Ashkezari, F. Fotouhi, M. Razmara, Experimental relationships between steel fiber volume fraction and mechanical properties of ultra-high performance fiber-reinforced concrete, J. Build. Eng. 32 (2020) 1–12.
[3] D.Y. Yoo, N. Banthia, Mechanical properties of ultra-high-performance fiber-reinforced concrete: a review, Cement Concr. Compos. 73 (2016) 267–280.
[4] F. Dingqiang, R. Yu, L. Kangning, T. Junhui, S. Zhonghe, W. Chunfeng, W. Shuo, G. Zhenfeng, H. Zhengdong, S. Qiqi, Optimized design of steel fibres reinforced ultra-high performance concrete (UHPC) composites: towards to dense structure and efficient fibre application, Construct. Build. Mater. 237 (2021) 1–13.
[5] C. Fang, M. Ali, T. Xie, P. Visintin, A.H. Sheikh, The influence of steel fibre properties on the shrinkage of ultra-high performance fibre reinforced concrete, Construct. Build. Mater. 242 (2020) 1–12.
[6] M. Gesoglu, E. Guneyisi, G.F. Muhyaddin, D.S. Asaad, Strain hardening ultra-high performance fiber reinforced cementitious composites: effect of fiber type and concentration, Composites Part B 103 (2016) 74–83.
[7] G.F. Muhyaddin, Fiber Reinforced UHPC and its Effects on Load Carrying Capacity of Composite Tube Members According to Current Design Codes, Phd Dissertation, Gaziantep University, Turkey, 2017.
[8] P. Rossi, A. Arca, E. Parant, P. Fakhria, Bending and compressive behaviours of a new cement composite, Cement Concr. Res. 35 (2005) 27–33.
[9] W. Meng, K.H. Khayat, Effect of hybrid fibers on fresh properties, mechanical properties, and autogenous shrinkage of cost-effective UHPC, J. Mater. Civil Eng. 30 (2018) 1–9.
[10] Z. Wu, C. Shi, K.H. Khayat, Investigation of mechanical properties and shrinkage of ultra-high performance concrete: influence of steel fiber content and shape, Composites Part B 174 (2019) 1–12.
[11] S. Kwon, T. Nishiwaki, T. Kikuta, H. Mihashi, Development of ultra-high-performance hybrid fiber-reinforced cement-based composites, ACI Mater. J. 111 (2014) 309–318.
[12] T. Oh, I. You, N. Banthia, D.Y. Yoo, Deposition of nanosilica particles on fiber surface for improving interfacial bond and tensile performances of ultra-high-performance fiber-reinforced concrete, Composites B 221 (2021), 109030.
[13] J. Yang, B. Chen, C. Nuti, Influence of steel fiber on compressive properties of ultra-high performance fiber-reinforced concrete, Construct. Build. Mater. 302 (2021) 1–12.
[14] N.E. Amanjean, M. Mouret, T. Vidal, Effect of design parameters on the properties of ultra-high performance fibre-reinforced concrete in the fresh state, Construct. Build. Mater. 224 (2019) 1007–1017.
[15] W. Meng, K.H. Khayat, Effect of hybrid fibers on fresh properties, mechanical properties, and autogenous shrinkage of cost-effective UHPC, J. Mater. Civil Eng. 30 (2018) 1–9.
[16] W. Meng, M. Valipour, K.H. Khayat, Optimization and performance of cost-effective ultra-high performance concrete, Mater. Struct. 50 (2017) 29.
[17] K. Wille, D.J. Kim, A.E. Naaman, Strain hardening UHP-FRC with low fiber contents, Mater. Struct. 44 (2011) 583–598.
[18] D.J. Kim, A.E. Naaman, S. El-Tawil, Comparative flexural behavior of four fiber reinforced cementitious composites, Cem. Concr. Compos. 30 (2008) 917–928.
[19] D.J. Kim, S.H. Park, G.S. Ryu, K.T. Koh, Comparative flexural behavior of hybrid ultra high performance fiber reinforced concrete with different macro fibers, Construct. Build. Mater. 25 (2011) 4144–4155.
[20] D.Y. Yoo, S.W. Kim, J.J. Park, Comparative flexural behavior of ultra-high-performance concrete reinforced with hybrid straight steel fibers, Construct. Build. Mater. 132 (2017) 219–229.
[21] Y. Niu, J. Wei, C. Jiao, Crack propagation behavior of ultra-high-performance concrete (UHPC) reinforced with hybrid steel fibers under flexural loading, Construct. Build. Mater. 294 (2021), 123510.
[22] E.T. Dawood, R. Mahyuddin, Mechanical properties of high strength flowing concrete with hybrid fibers, Construct. Build. Mater. 28 (2012) 193–200.
[23] B. Chun, D.Y. Yoo, Hybrid effect of macro and micro steel fibers on the pullout and tensile behaviors of ultra-high-performance concrete, Composites B (2019) 344–360.
[24] A.C. Mpalaskas, T.E. Matikas, D.G. Aggelis, N. Alver, Acoustic emission for evaluating the reinforcement effectiveness in steel fiber reinforced concrete, Appl. Sci. (2021) 3850, https://doi.org/10.3390/app11093850.
[25] V.K. Kytinou, C.E. Chalioris, C.G. Karayannis, Analysis of residual flexural stiffness of steel fiber-reinforced concrete beams with steel reinforcement, Materials 13 (2020) 2698, https://doi.org/10.3390/ma13122698.
[26] N. Kachouh, T. El-Maaddawy, H. El-Hassan, B. El-Ariss, Shear response of recycled aggregates concrete deep beams containing steel fibers and web openings, Sustainability (2022) 1945, https://doi.org/10.3390/su14020945.
[27] I.Y. Hakeem, M. Amin, B.A. Abdelsalam, B. Tayeh, F. Althoey, I.S. Agwa, Effects of nano-silica and micro-steel fiber on the engineering properties of ultra-high performance concrete, Struct. Eng. Mech. 82 (3) (2022) 295–312.
[28] S. Kwon, T. Nishiwaki, T. Kikuta, H. Mihashi, Development of ultra-high-performance hybrid fiber-reinforced cement-based composites, ACI Mater. J. 111 (2014) 309–318.

[29] P. Yan, B. Chen, S. Afgan, M.A. Hague, M. Wu, J. Han, Experimental research on ductility enhancement of ultra-high performance concrete incorporation with basalt fibre, polypropylene fibre and glass fibre, Construct. Build. Mater. 279 (2021), 122489.

[30] TS EN 197-1, Cement- Part 1: Composition, Specifications and Conformity Criteria for Common Cements, Turkish Standards, Turkey, 2002.

[31] ASTM C494/C494M-13, Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA, 2013.

[32] ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standard, 2012.

[33] ASTM C496, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standard, 2011.

[34] ASTM C469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, Annual Book of ASTM Standard, 2010.

[35] Recommendation, RILEM Draft, Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams, Mater. Struct. 106 (1985) 285–290.

[36] B.S. Mahdi, Properties of Self Compacted Reactive Powder Concrete Exposed to Saline Solution, Ph.D. Thesis, University of Technology, Baghdad, 2009.

[37] S.H. Iqbal, A. Ali, K. Holschemacher, A. Thomas, Mechanical properties of steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC), Construct. Build. Mater. 98 (2015) 325–333.

[38] R. Yu, P. Spiesz, H.J. Brouwers, Static properties and impact resistance of A green ultra-high performance hybrid fibre reinforced concrete (UHPHFRC): experiments and modeling, Construct. Build. Mater. 68 (2014) 158–171.

[39] J. Gao, W. Suqa, K. Morino, Mechanical properties of steel fiber-reinforced, high strength, lightweight concrete, Cem. Concr. Compos. 19 (1997) 307–313.

[40] M. Hassan Pour, P. Shafigh, H.B. Mahmud, Lightweight aggregate concrete fiber reinforcement: a review, Construct. Build. Mater. 37 (2012) 452–461.

[41] L. Hussein, L. Amleh, Structural behavior of ultra-high performance fiber reinforced concrete-normal strength concrete or high strength concrete composite members, Construct. Build. Mater. 93 (2015) 1105–1116.

[42] H. Yazici, The effect of curing conditions on compressive strength of ultra high strength concrete with high volume mineral admixtures, Build. Environ. 42 (2006) 2083–2089.

[43] M.H.A. Beygi, M.T. Kazemi, I.M. Nikbin, J.V. Amiri, The effect of water to cement ratio on fracture parameters and brittleness of self-compacting concrete, Mater. Des. 50 (2013) 267–276.

[44] S.T. Kang, Y. Lee, Y.D. Park, J. K Kim, Tensile fracture properties of an ultra high performance fiber reinforced concrete (UHPFRC) with steel fiber, Compos. Struct. 92 (2010) 61–71.

[45] M.E. Voutetaki, M.C. Naoum, N.A. Papadopoulos, C.E. Chalioris, Cracking diagnosis in fiber-reinforced concrete with synthetic fibers using piezoelectric transducers, Fibers 10 (2022) 5, https://doi.org/10.3390/fib10010005.

[46] A. Deifalla, A.G. Zapris, C.E. Chalioris, Multivariable regression strength model for steel fiber-reinforced concrete beams under torsion, Materials 14 (2022) 3889, https://doi.org/10.3390/ma14143889.

[47] S.H. Park, D.J. Kim, G.S. Ryu, K.T. Koh, Tensile behavior of ultra high performance hybrid fiber reinforced concrete, Cem. Concr. Compos. 34 (2012) 172–184.