ARTICLE IN PRESS

Ain Shams Engineering Journal xxx (xxxx) xxx

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Civil Engineering

Mechanical properties and ductility behavior of ultra-high performance fiber reinforced concretes: Effect of low water-to-binder ratios and micro glass fibers

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ARTICLE INFO

Article history:
Received 2 January 2020
Revised 12 May 2020
Accepted 1 November 2020
Available online xxxx

Keywords:
Micro glass fibers (MGF)
Mechanical properties
Fracture energy
Water-to-Binder ratio (w/b)
Ultra High Performance Fiber Reinforced Concrete (UHPFRC)

ABSTRACT

This experimental work investigates the mechanical performance and ductility behavior of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) containing high volume of micro-glass fibers (MGF). The influence of various volume fractions of MGF and two water-to-binder ratios (w/b) are investigated. These w/b ratios are 0.12 and 0.14. Based on these ratios, two groups of UHPFRC mixes were prepared and each group include seven mixes made with 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% MGF volume dosages. In total fourteen mixes were examined for the mechanical properties such as compressive strength, splitting tensile strength, modulus of elasticity, flexural strength; and the ductility behavior. It was concluded that lower w/b resulted in better mechanical performance. Also, the mixes containing 1.5% to 3% of MGF, resulted in the highest compressive strength reaching up to 160 MPa. Furthermore, the results indicated that no more strength enhancement can be achieved beyond 1.5% MGF.

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1. Introduction

The term "Ultra-High Performance Concrete" was first used by De Larrard and Sedran [1] and a similar development, Richard and Cheyrezy [2] used the term reactive powder concrete (RPC) in 1995. Since the late 20th century the concrete technology had experienced a significant development led to the production of Ultra-High Performance Concrete (UHPC) or Ultra-High Strength Concrete (UHSC), which has been the topic of most research related to concrete technology worldwide. The characteristics of UHPC make it an ultimate applicant for use in several construction components [3,4]. UHPC is composed of high binder content such as cement and silica fume, different types of fibers, and crushed quartz ranging between (10–2500) μm used to give uniformity instead of using conventional coarse [2,5–7]. Besides, UHPC is recognized by a meager water-to-binder ratio with enough workability which can be achieved with the help of a new generation of superplasticizers. The very low w/b ratio can result in a concrete with low permeability and hence improved durability and strength [8,9]. For instance, Serelis et al. [10] were able to enhance the strength of concrete under compression load from 119 MPa to 145 MPa via decreasing w/b from 0.28 to 0.22. Studies have reported, mechanical properties of UHPC including the results of compression test, flexural, splitting test were >150 MPa, between (30–60) MPa and >7 MPa, respectively, and Young's modulus reached to 60 GPa [2,11,12]. Bahedh and Jaafar [13] investigated on UHPC with water/cement of 0.24, high binder content of 657 kg/m^3 and a Quarry dust of 1050 kg/m^3 with Maximum size (150 μm–1.18 mm) in saturated surface dry condition. To achieve a good workability 40 kg/m^3 of superplasticizer was used. The maximum compressive strength that achieved was 122.4 MPa.

Due its high brittleness, UHPC displays low in tensile strength and undesired ductility. This has created barriers against the wide spread of the use of such type of concrete in many applications. To overcome these barriers, studies have been conducted to examine

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Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.asej.2020.11.008
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Please cite this article as: B.H. Mohammed, Aryan Far H. Sherwani, R.H. Faraj et al., Mechanical properties and ductility behavior of ultra-high performance fiber reinforced concretes: Effect of low water-to-binder ratios and micro glass fibers, Ain Shams Engineering Journal, https://doi.org/10.1016/j.asej.2020.11.008

the effect of using fibers with different types and characterizations on the mechanical performance of plain UHPC. UHPFRC is a composite material that comprises the plain UHPC with different kinds of fibers which can enhance the mechanical properties and fracture behavior in a progressive manner. Many researchers have proved the utilization of fibers significantly develops the properties of concrete such as toughness, flexural strength, fatigue resistance, impact and abrasion resistance, load bearing capacity after cracking and post-cracking capacity, deformation capability and tensile strength [5–7]. Mainly, UHPFRC represents the highest development of UHPC, and its ultimate compressive strength could be as high as 800 MPa depending on the w/b ratio and curing conditions [2]. Some parameters that negatively affects the workability of UHPFRC such as: w/b ratio, high cement content, silica fume and steel fibers. To attain a constant slump value superplasticizer in variable amounts was used. So as to keep the superplasticizer request, a relatively high w/b of 0.195 was used. Whereas to achieve a workable batch with low w/b utilizing superplasticizer could be a good choice [14–16].

There are limited works on the UHPFRC to optimize the volume fraction of MGF. Although, Many researchers have examined the performance of UHPFRC so as to determine the fiber properties such as; fiber type, volumetric content, distribution homogeneity, length and types of steel fibers [17–19]. Tran et al. [20] showed the enhancement of fracture parameters of UHPFRC by adding 1–1.5% fibers. They determined that smooth fibers displayed higher fracture strength than twisted fibers. Many attempts has been done to improve the performance of UHPC using fibers with altered characteristics. Glass fibers (GF) are relatively lightweight, high in tensile strength, and cheap. There are limited study on utilizing of MGF in UHPC despite some studies on their effect on conventional concrete. Also, researchers had shown when GF added into a standard concrete matrix it could increase the flexural, and tensile strengths with improving the post-peak ductility in compression [21,22]. Furthermore, Chandramouli et al. [23] observed that 20–25% of compressive strength and 15–20% of splitting and flexural strength were increased when they reinforced concrete by using GF. Also, Tassew and Lubell [24] observed that with increasing MGF, the flexural strength value of concrete improved. Hannawi et al. [25] inspected on the effect of utilizing different types of fibers on the microstructure and the mechanical behavior of the UHPFRC, the experimental values showed that fibers has a relatively slight influence on the compressive strength and elastic modulus of concrete, except for the steel fiber which improves the strength because of its inherent rigidity. It was also reported that UHPFRC is very strong, ductile and durable compared to the normal concrete [26].

The main purpose of the present study is to optimize the volume fraction of MGF through investigating the mechanical properties and ductility behavior of Ultra-High Performance Concretes reinforced with glass fibers (HPFRC). For the production of UHPFRC, two groups of UHPC were designated for the low w/b of 0.12 and 0.14. Each group contains seven mixes made with MGF at contents of (volume fractions) 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%. The strengths of UHPFRC were assessed through the following tests: modulus of elasticity, compressive strength, flexural strength, and tensile strength. Also, the ductility of UHPFRC was evaluated through fracture parameters.

2. Experimental program

2.1. Materials

In the current work, OPC (CEM, I 42.5 R) cement was utilized in ultra-amount meeting the requirements of the TS EN-97 [27] (mainly based on the European EN 197-1), and Silica fume (SF) was used as supplementary cementitious materials. Silica fume (SF) is the most commonly used amorphous silica as a cementitious matrix, which owns an average particle size of about 10 times lower than that of cement. It has been used in the ranges of 10–25% by weight of cement since last 60 years, therefore its pozzolanic and filling properties on the concrete properties have been broadly recognized [28]. Table 1 provides the physical properties as well as chemical composition of the PC and SF. Commercial quartz in three different size fractions of 1.2–2.5 mm, 0.6–1.2 mm and 0–0.4 mm with a specific gravity of 2.65 were used as fine aggregates. In order to achieve the workability specifications, a new-generation superplasticizer (SP) that named as a type of polycarboxylate was utilized in different amounts to maintain the target workability for the mixtures. MGFs of 13 mm length and diameter of 18 μm were used as fiber reinforcement. The properties of MGFs as given by the producer are listed in Table 2.

2.2. Mixing proportions and casting

The composition of UHPFRC mixes investigated in the present study are characterized with high volume of binder and MGFs, free of coarser aggregate, and extremely low w/b ratio such as many other studies [29–32]. The examined parameters in the current study are w/b ratio and MGF content. Table 3 presents the 14 mixtures of UHPC, divided into two groups based on the w/b that designed and produced (0.12 and 0.14). In both groups, the silica fume content was fixed at 15% by weight of total cementitious materials. Micro glass fibers at volume ratios of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% for each group were used. The first column in Table 3 represents the code of the mixture which include the w/b ratio and the content of MGF; for example, mix 0.12MGF0.5 denotes the mix of UHPFRC at 0.12 w/b reinforced with 0.5% MGF volume fractions.

For producing UHPC, a high speed vertical axis mixing machine having a maximum speed of 470 rpm was used. Firstly, the binder and the quartz aggregate were mixed in the machine at low rate of 100 rpm for three minutes. After that 75% of the water was used to the mixture and remixed for another four minutes at the same speed. Then SP and the rest water were poured into the batches and mixed for 5 min. Last part of the of mixing process included adding the MGF and all materials were mixed for more two minutes at 100 rpm speed and an extra two minutes at a rate of 470 rpm. The fresh mixtures were then poured into the molds of varies sizes; three cubic specimens of 50^3 mm, three cubic specimens of 70^3 mm, three cubic specimens of 150^3 mm, and three prisms of dimension's $70 \times 70 \times 280$ mm to determine mechanical properties and ductility behavior. After that, the molds were com-

Table 1
Chemical compositions and physical properties of OPC and SF.

Item	Cement	Silica Fume
$Fe2O3$	2.88	1.31
SO3	2.63	0.41
K2O	0.88	1.52
CaO	62.12	0.45
MgO	1.17	–
SiO2	19.69	90.36
Na2O	0.17	0.45
CI	0.0093	–
Al2O3	5.16	0.71
Free CaO	1.91	–
Specific surface (m^2/kg)	394	21,080
Insoluble residue	0.16	–
Loss on ignition	2.99	3.11
Specific gravity	3.15	2.2

Table 2
Properties of glass fiber.

Fiber type	Length (mm)	Diameter (μm)	Modulus of elasticity (GPa)	Elongation (%)	Tensile Strength (MPa)	Aspect ratio (L/d)	Density (g/cm^3)
Micro Glass	13	18	77	2.56	2000	722	2.60

Table 3
Mix proportions (kg/m^3).

Concrete mixture	w/b	Cement (kg/m^3)	Silica fume (kg/m^3)	Water (kg/m^3)	SP (kg/m^3)	Glass fiber %	Quartz aggregate (kg/m^3)
0.12MGF0	0.12	998.8	176.25	141.0	75.2	0.0	1010.1
0.12MGF0.5	0.12	998.8	176.25	141.0	77.6	0.5	991.1
0.12MGF1.0	0.12	998.8	176.25	141.0	78.7	1.0	975.0
0.12MGF1.5	0.12	998.8	176.25	141.0	81.7	1.5	954.5
0.12MGF2.0	0.12	998.8	176.25	141.0	82.8	2.0	942.7
0.12MGF2.5	0.12	998.8	176.25	141.0	84.6	2.5	920.8
0.12MGF3.0	0.12	998.8	176.25	141.0	88.2	3.0	898.7
0.14MGF0	0.14	998.8	176.25	164.5	49.4	0.0	1013.9
0.14MGF0.5	0.14	998.8	176.25	164.5	49.4	0.5	998.0
0.14MGF1.0	0.14	998.8	176.25	164.5	50.5	1.0	981.9
0.14MGF1.5	0.14	998.8	176.25	164.5	52.9	1.5	962.9
0.14MGF2.0	0.14	998.8	176.25	164.5	54.1	2.0	946.8
0.14MGF2.5	0.14	998.8	176.25	164.5	55.2	2.5	930.6
0.14MGF3.0	0.14	998.8	176.25	164.5	62.3	3.0	900.1

pacted by using a vibrator machine then wrapped with nylon sheets and left to cure under room temperature. The molds of the samples were removed one day after process of casting and then water curing selected until the test date. Furthermore, despite using very low w/b ratios in the current research study that were smaller than the ratio chosen by most of the other researchers yet good UHPC flow of 18 ± 1 cm were produced. Yoo et al. [33] studied on the UHPFRCs. The w/b was 0.2 with steel fibers of 2% volume, 13 mm in length and 0.2 mm in diameter was utilized and 23 cm flow was obtained.

2.3. Testing procedures

Cubes with dimensions of 50*50*50 mm were used for the compression test according to BS 1881-116 [34]. This test was conducted at ages of 7, 14, and 28 days. Three samples were tested for each mixture, and the average pf these tree samples was recorded. The splitting test was carried concerning BS 1881-117 [35] on 70 mm cubes at 28 days. 150 mm Cubic specimens were used for determining the elastic modulus following BS EN 1352 [36]. The samples were loaded up to the load level of 40% for the maximum load that is obtained from the compressive strength test; corresponding stress was found from it, and the elastic modulus was reported as the average of the three sets of readings, using the stress–strain response.

Fracture energy behavior of UHPFRC was obtained according to the specifications and recommendations of the RILEM 50-FMC [37]. A closed-loop of 250 KN capability machine was utilized. See Fig. 1

Fig. 1. Front view of notched beam specimen.

for the test details and sample setting. A linear variable displacement transducer (LVDT) was attached to specific samples to record the displacement (δ) in the middle of the span. The fracture energy (G_F) define as area below the curve (Wo) was found after getting the load–displacement curve. The equation was used as follows:

$$G_F = \frac{W0+mgA}{BL} \quad A = \delta_s \frac{s}{u};\ L = (W - a) \tag{1}$$

where S is the length, W is the depth, B is the width, a is the notch depth, U is the span length, m is mass, δs is the beam displacement, and g is the acceleration of gravity. For prisms the loading rate was 0.02 mm/min. The net flexural strength (fflex) was measured via Eq. (2) where Pmax is the critical load by supposing no notch sensitivity [38,39]. Furthermore, characteristic length (lch) was obtained by using Eq. (3) where fst referred to the splitting tensile strength [40]. The characteristic length (lch) was used as an indicator to assess the ductility of the concrete mixes.

$$f_{flex} = \frac{3P_{max}S}{2BL^2} \tag{2}$$

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

3. Results and discussion

3.1. Compressive strength

The outcomes of the compressive strength at ages 7, 14 and 28 days for all UHPCFRCs mixes are shown in Fig. 2. These figures illustrate the influence of MGFs content on the compressive strength of UHPC for 0.12 and 0.14 w/b ratios.

The obvious influence of w/b on the results of compressive strength of the plain UHPC mixes is clear. At all ages, it can be seen that the plain concrete mix made with w/b ratio of 0.12 shows higher strength than that of 0.14 w/b ratio. Such inverse relation between w/b and compressive strength is also reported by other studies [10,41,42]. Moreover, the strength that is gained due to water curing was observed higher at the ages of 14 days and 28th days in comparison to the 7 day of water curing. For example, the compressive strength at the ages of 14 and 28 days were higher

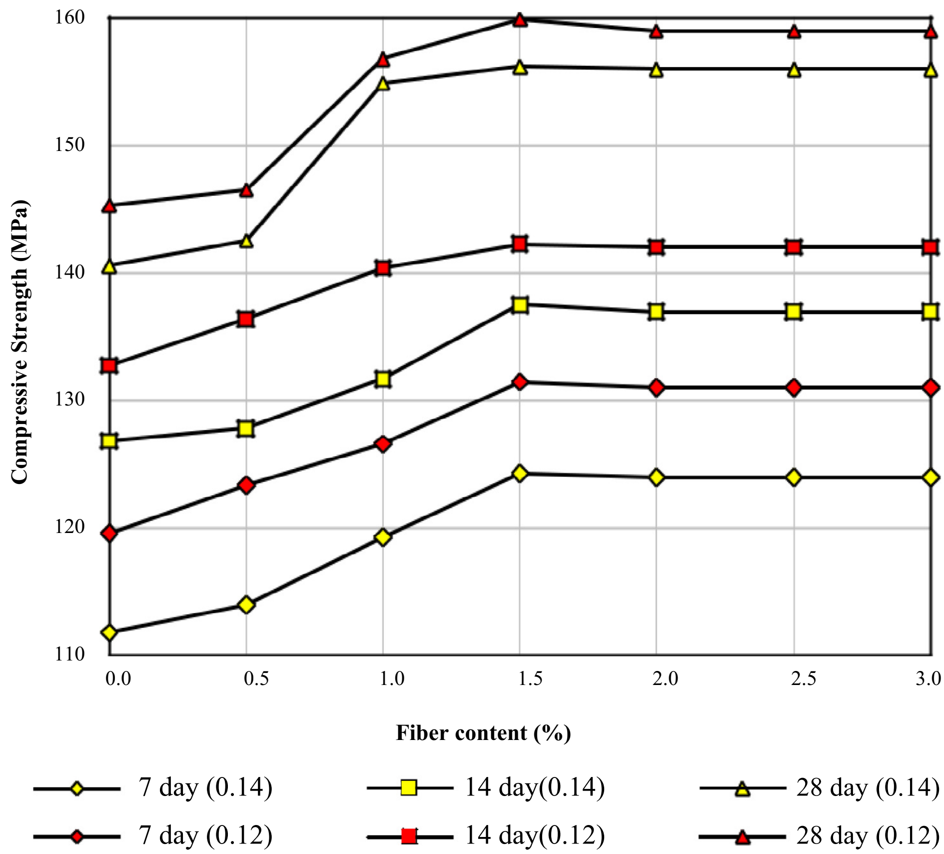

Fig. 2. Compressive strength of UHPC of different ages for the 0.12 and 0.14 w/b.

by 8.3% and 21.7% for the mixes with 0.12 w/b and by 10.6% and 25.7% for the mixes with 0.14 w/b ratio than that of the 7 days, respectively. Moreover, the reduction in strength observed in the UHPCs with increasing w/b ratio may be attributed to formation of further unwanted calcium hydroxide particles during the hydration process.

Fig. 2 shows that out of the two groups of UHPFRC mixes, the highest compressive strengths were obtained at the group of 0.12 w/b, even the differences were slightly small. The figure also indicates that there is an effective improvement in strength by raising the fiber content until 1.5%; whereas beyond this fiber content this strength enhancement stays at a certain level, irrespective to w/b and age. As soon as the fiber content raised from 0% to 1.5%, the improvement in compressive strength reached 10%, and 11.1% for 0.12, and 0.14 w/b, respectively. This is probably due to the excessive numbers of fibers in the mixture. With increasing MGF for more than 1.5%, there was no effect on the compressive strength. The above mentioned behavior could be due to the high content of fibers mean large number of fibers which may result in the development of micro-voids in the concrete during the mixing procedure leading to diminish of strength enhancement because of the existing of higher number of fibers.

3.2. Splitting tensile strength

The splitting tensile mechanism of failure is not comparable to compressive strength since the splitting tensile failure path spreads throughout the aggregates and cement paste rather than interfacial transition zone (ITZ) as a result of the strong bonds between them [43,44]. Also, the Fiber reinforced concrete tensile behavior can be distributed into two classes: pre and post-cracking. The earlier behavior is commonly influenced by the elastic shear transfer mechanism among the fiber and the matrix. Whereas the latter one is stated by the collective effect of fiber bridging and matrix tension softening behaviors [45]. Typically, the addition of fibers develops the concretes tensile strength. This is due to that the fibers enables to block tensile cracks and then restricting crack growth [54].

The results of splitting tensile strength for the two groups of mixes having various volumes of MGF are known in Fig. 3. The strength development of the splitting tensile strength is parallel to that obtained in the compressive strength. Just as the compressive strength, the batches with lower w/b showed higher tensile splitting strength. The splitting tensile strengths of the plain concretes were 9.2 MPa for the mix with 0.12 w/c ratio and 8.3 MPa for the mix with 0.14 w/b ratio. It seems that the addition of the MGF enhanced the splitting tensile strength up to a certain volume fraction of fibers. For instance, adding MGF from 0.0% to 1.5% leads to an increase in the strength value by 27.7% and 27.3% for 0.12 and 0.14 w/b ratios, correspondingly. Similar to the compressive strength, it was noticed that no significant enhancement in splitting strength for the UHPFRC was achieved with increasing the MGF content beyond the 1.5%, irrespective to its water content. This behavior could be due to that with small number of fibers at low content of MGF the matrix reaches a high level of packing which in turn improves the ITZ leading to high strength; whereas at high content of MGF, the large number of fibers could reduce the contribution of fibers in enhancing the strength due to the possible development of the micro voids developed during the mixing process of the concrete.

3.3. Modulus of elasticity

The static elastic modulus of UHPC for various volume fractions of MGF made with the two groups of water-to-binder ratios at 28-day curing are shown in Fig. 4. It was observed the modulus

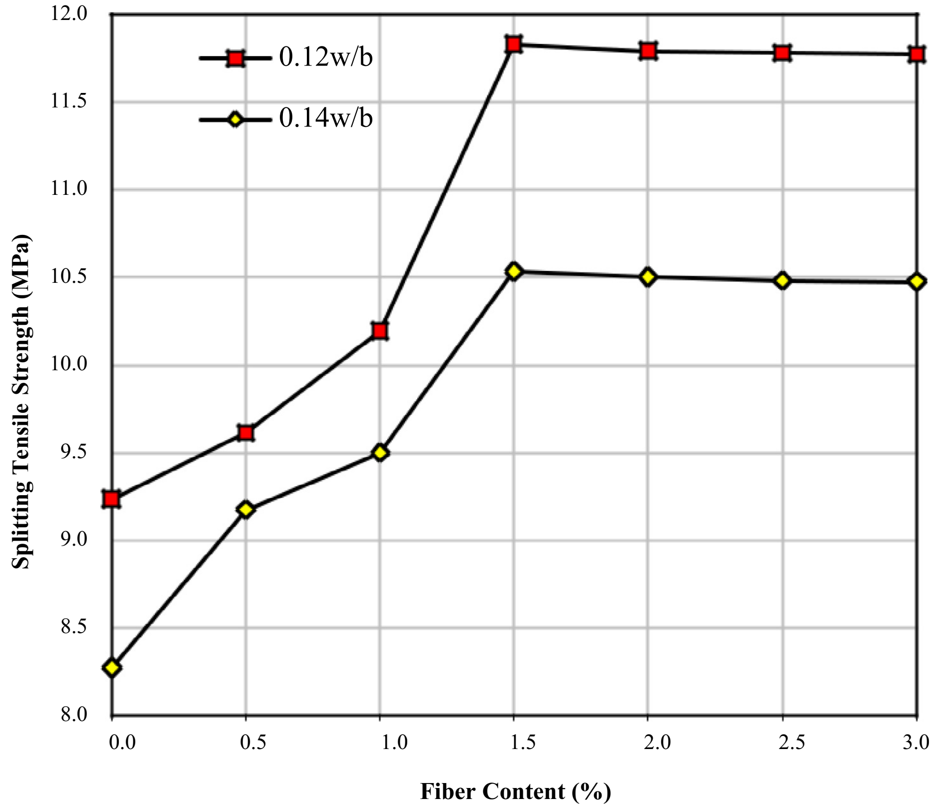

Fig. 3. Splitting tensile strength of UHPC versus different volume of micro glass fiber at 28 days.

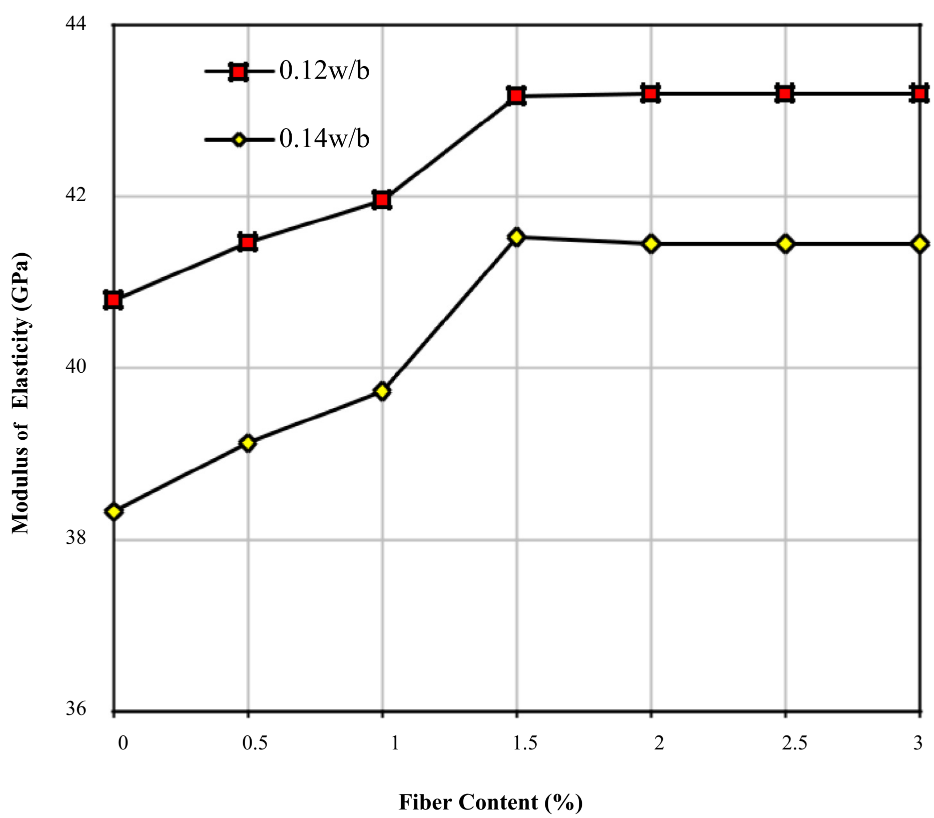

Fig. 4. Modulus of Elasticity of UHPC versus different volume of micro glass.

of elasticity for UHPC was improved by adding fibers [46]. In this study, it was observed that there is a slight variance between the results of the two groups of w/b ratios. Regardless of the water-to-binder ratios, it was observed that by adding MGF the static elastic modulus of the UHPC increased systematically up to a volume fraction content of MGF (1.5%). After Beyond that certain limit of fibers dosage, results showed no variations, possibly due to an excessive number of fibers that have led to no more enhancement due to the possible reduction in the well packing between aggregate particles, fibers and the matrix. The mixes of UHPFRC had improvement by 5.8% and 8.3% at 1.5%, comparing to their references for the first and second groups, correspondingly. These results indicate that UHPFRC mixes with an optimized dosage of micro-glass fibers could result in a high stiffness UHPFRC. Furthermore, based on the experimental results, the stiffness of UHPFRC increased up to a certain limit of MGF content then no significance variation in stiffness has been observed. This maximum can be explained by the effect of the well packing of the ingredients of the concrete and the good bond between the cement paste matrix and particles of aggregates. Also, the well distribution of the micro fibers could lead to the delay of the propagation of the micro cracks resulting in high stiffness. Moreover, the reason for modulus of elasticity to remain constant after adding 1.5% of MGF could be attributed to the existence of too much of micro fibers (Fig. 5) that might disturb the packing of the concrete and weakens the bond between the aggregate particles and the cement matrix.

Fig. 5. Micro glass fiber.

3.4. Modulus of rupture

Fig. 6 shows the results of net flexural strength (moduli of rupture) of UHPFRC under three-point bending. The outcomes of this experimental work are in good agreement with earlier works on improving the flexural strength of UHPCs, since the fibers were utilized, particularly existing in large volume fractions. [24,40]. Indeed, there was relatively enhancement in the net flexural strength of UHPFRC with adding 3% of MGF to reach its maximum value of 17.7 MPa and 16 MPa at 28-day water curing for the 0.12 and 0.14 w/b, respectively. Increment in the modulus of rupture may be refers to enhancing the connection between aggregate particles and cement matrix through the help from small well-distributed glass fibers (Fig. 4). Furthermore, more energy is needed to make a crack in UHPFRC as a result of the substantial capacity of the high volume of glass fibers to absorb most energy under bending. On the other hand, the percentage of MGF was more effective on the modulus of rupture of the produced UHPFRC than the water-to-binder ratios. For instance, the average enhancement in the net flexural strength with adding 3% of MGF to plain UHPC was 60.1% for the 0.12 w/b, whereas decreasing of w/b from 0.14 to 0.12 causes an improvement by 10.7% for the same content of MGF.

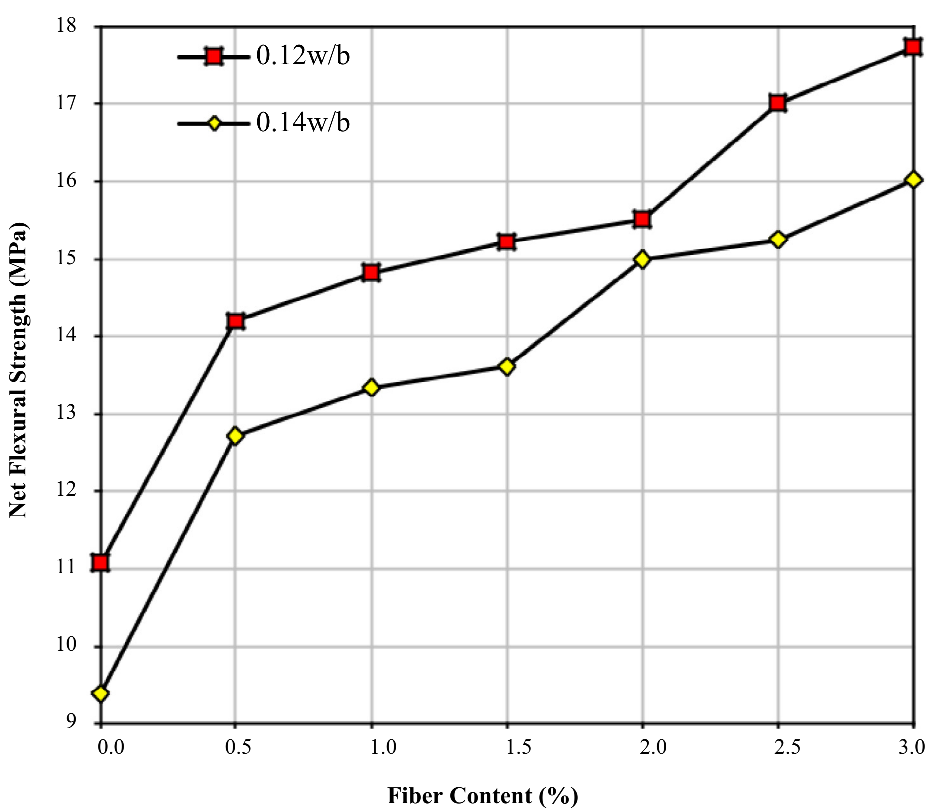

Fig. 6. Net flexural strength of UHPC versus different volume of micro glass fiber at 28 days.

3.5. Load-displacement curves

The load–displacement curves for the notched beam of UHPC with various percentages of volume fraction of MGF for the w/b of 0.12 and 0.14 ratios as in Fig. 7 a & b. Also, Table 4 presents the influences of w/b and different volume fractions of fibers on parameters such as: area under the load–displacement curve, maximum displacement, and peak load. When the test starts, initially the applied load is sustained by the intact matrix of UHPC up to a certain level of load; thereafter the MG fibers start to be effective and help in carrying the load named as the peak load. The peak load denotes as the maximum load of the load–displacement curve. Nevertheless, as much as the composite of UHPFRC subjected to a load more significant than its capacity, the first crack would appear, and the subjected load consecutively decreases as the short fibers no longer resist the propagation of the cracks [47]. Unquestionably, existing huge numbers of well-distributed MGF in the plain UHPC result in extent the slope of the pre-peak and post-peak of the curve due to bridging the micro-cracks of the UHPC. Likewise, the MGF content increased the toughness of the composite concrete due to increasing the area under the curve and the maximum load that can be carried. MGF could delay the development of the micro-cracks and can arrest them after their development. However, when these micro cracks propagate and become macro-cracks under loading, the short MG fibers are no longer active leading to the failure of concrete (See Fig. 4). The addition of fibers significantly reduces the lateral strain at peak loading and increases the threshold of initial cracking. Therefore, the fibers clearly confine the cracking progression in concrete under the mechanic loading [25].

The UHPFRC containing 3% MGF with 0.12 w/b had an area under the curve, a maximum displacement, and a peak load of 1557.4 kN·mm, 1.5 mm, and 7.3 kN, respectively, whereas these values decreased to 1315.7 kN·mm, 1.4 mm, and 6.6 kN with mix prepared with 0.14 w/b. This decline in the fracture parameters indicates that any extra water may play a passive role to restrict improving ITZ, de-bonding between aggregate and binder, and obstructing fibers to bridge the micro-cracks. The significance of decreasing w/b and its effects on the microstructure of concrete, in general, were also approved by the others [15,16,48,49].

3.6. Fracture energy (Gf)

Despite having the central role in determining ultimate stress at the crack tip, fracture energy is a function of the displacement and not the strain. It can be expressed as the energy required to open the unit area of the crack surface. However, the fracture parameters specify the ductility behavior of concrete, the higher the concrete ductility, the greater is the Gf.

Table 4
Load - displacement test results.

Concrete mixture	area under the curve (kN·mm)	maximum displacement (mm)	P max (kN)
0.12MGF0	261.2	0.9	4.6
0.12MGF0.5	364.2	0.9	5.8
0.12MGF1.0	460.6	0.9	6.1
0.12MGF1.5	629.5	1.0	6.3
0.12MGF2.0	895.5	1.1	6.4
0.12MGF2.5	1033.9	1.2	7.0
0.12MGF3.0	1315.7	1.5	7.3
0.14MGF0	471.7	0.73	3.9
0.14MGF0.5	592.7	0.95	5.2
0.14MGF1.0	888.0	1.01	5.5
0.14MGF1.5	1236.2	1.02	5.6
0.14MGF2.0	1350.6	1.09	6.2
0.14MGF2.5	1391.	1.12	6.3
0.14MGF3.0	1557.4	1.42	6.6

In the current study in Fig. 8, the total fracture energy of UHPFRC is affected by the two significant investigated factors; w/b and volume fraction of the MGFs. It can be seen that the Gf is directly related to the content of the MGF regardless of w/b ratio. However, the effect of the addition of MGF has more positive effect on the values of Gf of the mixes made with 0.12 w/b than the mixes made with 0.14 w/b. The results also show that the UHPC with 3% MGF content exhibit the maximum value of the fracture energy, irrespective of water content. For instance, adding 3% of micro glass fibers to plain UHPC led to an improvement in the Gf by 211.4% and 370.6% for the 0.12 and 0.14 w/b, subsequently. The high performance of MGF in showing significant enhancement in the Gf may be related to their main properties like high-tensile strength and aspect ratio as seen in Table 4, which necessities high energy to fracture the prisms due to arresting cracks and energy absorbing by these microfibers. Furthermore, it can be concluded that because of the ability to bridge the micro-cracks and delaying the propagation of the micro cracks to macro cracks, the micro glass fiber-reinforced UHPCs have more considerable fracture energy [50].

3.7. Characteristic length

As long as the rate of characteristic length (lch) is high, the concrete become less brittle because it is a measurement of brittleness

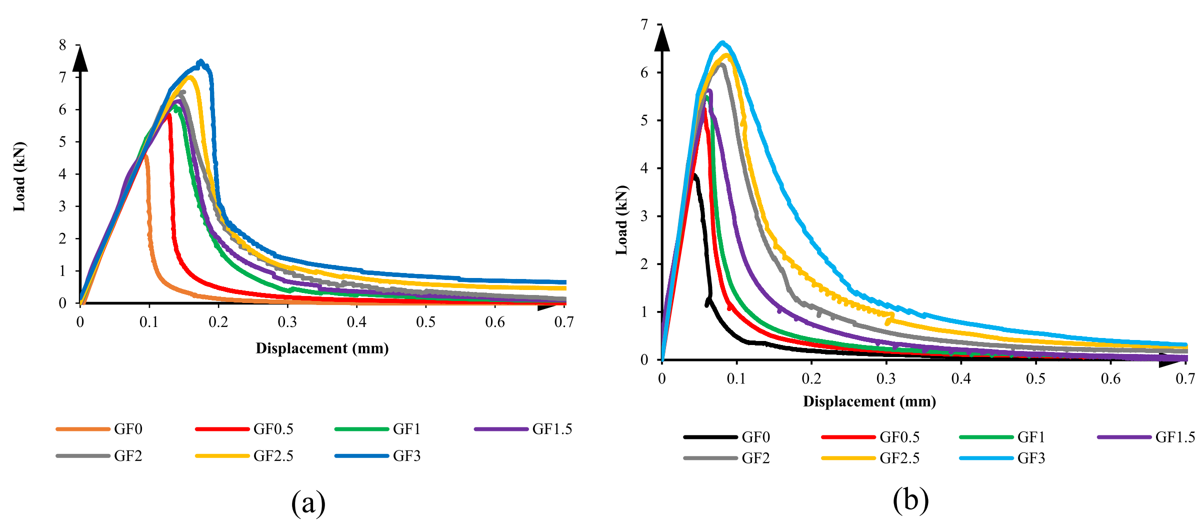

Fig. 7. Load-displacement curves of UHPFRC with regards to MGF content: (a) 0.12 w/b (b) 0.14w/b group.

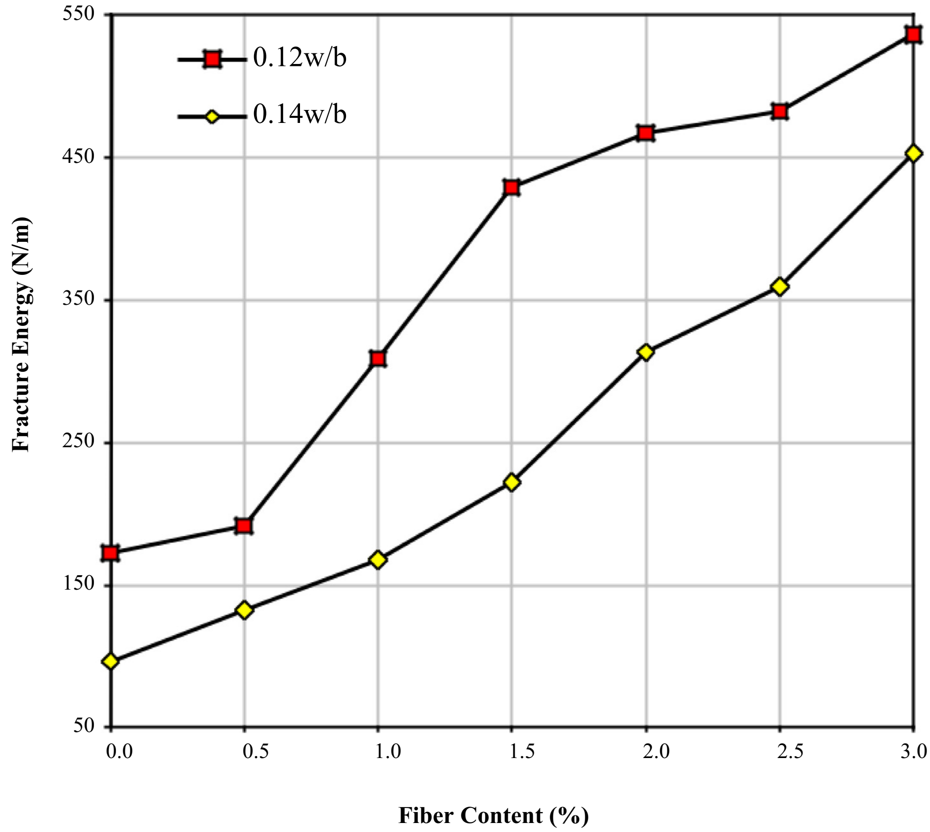

Fig. 8. Fracture energy versus different MGF rates of UHPFRC at 28 days.

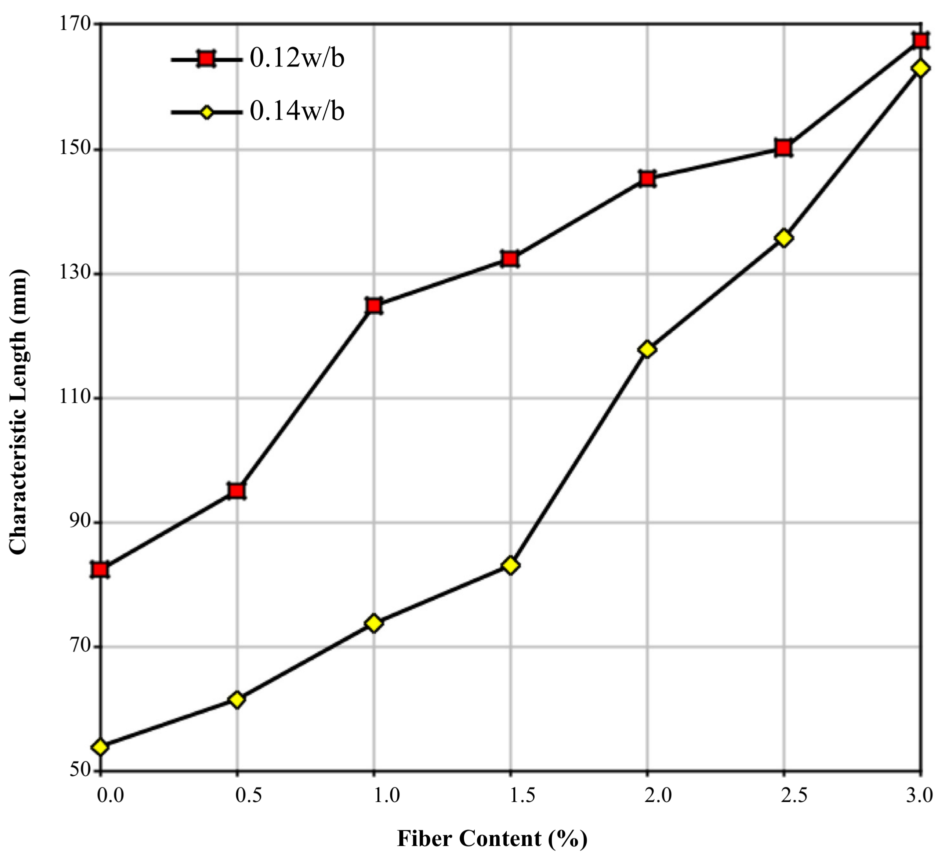

Fig. 9. Characteristic length versus different glass fiber rate of UHPFRC at 28 days.

of concrete. Additionally, according to Eq. (3), the characteristic length depends directly on some essential mechanical properties of UHPFRC like fracture energy and elastic modulus and inversely on the tensile strength.

The results of the characteristic length of UHPC reinforced with different volume of MGFs and two water-to-binder contents of 0.12 and 0.14 are shown in Fig. 9. Lower w/b displays higher values of lch as can be seen in Fig. 9. Regardless of the w/b ratio, the addition of MGF resulted in more ductile UHPCFRC than the plain UHPC due to the higher values of the lch of the mixes reinforced with MGF comparing to those of the plan mixes. Nonetheless, the arte of the increase in the lch due to adding MGF for the mixes made w/b of 0.14 is higher than the mixes of 0.14 w/b ratio.

It can be seen that even small dosage of fibers led to enhancement in the lch. Also, it is clear that the differences in the measured lch of the UHPFRC become lesser between the two groups when the volume dosage of micro glass fibers ranged between (2–3) percent. This could be attributed to a vast number of fibers at high surface area, which will not let water to play an essential role in effecting of ductility of UHPCs. However, compared to the study of Gesoglu et al. [46] (where the w/b was 0.195 and the fibers had l = 13 mm and d = 0.018 mm) there is a significant improvement of the brittleness of UHPC by adding MGFs. The maximum value that they achieved was nearly 48 mm for the plain concretes without fibers. Whereas, for the plain UHPC the value of the lch were 82.4 mm and 54 mm for the 0.12 and 0.14 w/b, consecutively. This could be due to the difference in the composition and w/b ratios used in this study. In the current study, by adding MGF up to 3%, the characteristic lengths of 167.4 mm, and 163 mm were recorded for the prisms of the same dimensions (70 × 70 × 280) mm for the first and second groups, consequently. Zhang et al. [51] measured the characteristic length between 412 and 235 mm, and Petersson [52] measured the characteristic length between the range of 200 and 500 mm. furthermore, for self-compacting high-strength concretes containing plastic it was found that lch ranged between 85 and 178 mm [53].

4. Conclusion

In this study, the influence of very low w/b and the addition of MGF on the performance of UHPC have been examined. The results obtained for the experiments can lead to the following conclusions:

1 The decline in strength observed in the UHPCs with increasing w/b may be attributed to the formation of further unwanted calcium hydroxide particles during the hydration process.
2 It was noted that there was a systematic growth in the compressive strength, tensile strength, and modulus of elasticity with increasing the fiber contents up to 1.5% and then the results of the mechanical properties indicated no more strength gaining. This behavior could be because of the vast number of fibers per the volume of the concrete as the fiber content increases.
3 The reason of the close results of the modulus of elasticity for the two w/b ratios could be related to small difference in the investigated values of the water-to-binder ratios. The addition of MGF improves the stiffness of the plain UHPC but to a certain content of MGF.
4 The increase in the content of the MG fibers has much more beneficial effect on the strength of UHPC than the influence of decreasing water content. For example, the average enhancement in net flexural strength with adding 3% of fibers to plain UHPC was 60.1% for 0.12 w/b group, whereas decreasing of w/b from 0.14 to 0.12 caused an improvement by only 10.7% for the same volume dosage of micro glass fiber.
5 The addition of MGF increases the value lch of the concrete even with small dosage of fibers. The differences in the measured lch of the UHPFRC become lesser between the two groups of w/b ratios when the MGF content ranged between (2–3) %. This could be due to a vast number of fibers at high surface area, which will not let water to play an essential role in effecting of the ductility of UHPCs.
6 More ductile UHPC can be obtained when MGF is added. The Gf increases as the content of the MGF increases regardless the w/b ratio. The high performance of micro-glass fibers may be related to their main properties like high tensile strength and aspect ratio, which made it need tremendous energy necessary to fracture the prisms due to arresting cracks. Furthermore, it was also observed that the toughness of the composite concrete was increased with utilizing the MGF due to increasing the area under the curve and the maximum load that can be carried.

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.

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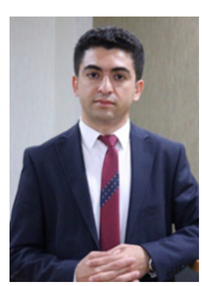

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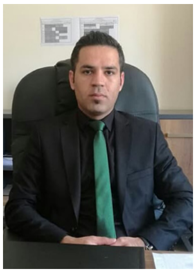

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