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Mechanical Properties of Ultra-high Performance Concrete Reinforced by Glass Fibers under Accelerated Aging

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ABSTRACT

Ultra-High Performance Concrete (UHPC) is a cementitious composite with fine aggregates and a homogeneous matrix with high compressive strength and excellent durability against aggressive agents. It is common to use short steel fibers in the UHPC. Besides, using steel fibers considerably increases the flexural ductility, durability and energy absorption. Using glass fibers in UHPC is a novel technique which improves its mechanical properties and it has the benefit of being lighter, and cheaper than steel fibers. Furthermore, glass fibers can be used for thin concrete plates for aesthetic purposes. However, glass fibers reinforced concrete is incompatible with the hydration reaction in the alkaline environment of concrete as it can damage glass fibers, so the mechanical properties of the concrete are decreased over long periods. The mechanical properties of UHPC containing glass fibers (GF-UHPC) was investigated under three regimes of normal curing, autoclave curing, and autoclave curing plus being in hot water for 50 days (accelerated aging). Besides, the substitution of silica fume by Metakaolin in GF-UHPC was studied to understand its mechanical properties after thermal curing. The results showed that after accelerated aging, the behavior of specimens become more brittle and the modulus of rupture and toughness indices of all prismatic specimens decreased, the modulus of rupture for samples containing glass fibers was 40% lower than autoclave curing results. However, the compressive strength under accelerated aging increased at least 4% in comparison to the normal curing. Replacement of silica fume with Metakaolin slightly increased the toughness with regard to flexural strength.

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NOMENCLATURE

I_5, I_{10}, I_{20}	Toughness Indices show the flexural strength and ductility of the specimen	δ	First-crack deflection
$R_{5,10}$,$R_{10,20}$	Residual strength factors are the strength retained after the first crack		

1. INTRODUCTION

One of the substantial achievements in concrete technology in the 20th century was the advance of ultra-high performance concrete (UHPC) or reactive powder concrete (RPC), more generally recognized as UHPC [1]. Small sand particle size (less than 0.6 mm), a high volume of cement (more than 600 kg/m^3), binder (Pozzolan, Metakaolin, Silica fume, Fly ash), and a minimum water/cement ratio (w/c $\leq$ 0.2) with high dosage of superplasticizer creates a solid matrix with high homogeneity and considerable compressive strength [2].

Plain concrete is a brittle material with low tensile strength and strain capacity; however, this troublesome property can be improved by adding short fibers to the matrix, which forestalls or controls the initiation or spreading of cracks [3]. Adding fibers to the matrix of concrete has many benefits, such as improving durability, bearing capacity, tensile capacity and toughness compared to plain concrete [4].

The reasons for using glass fibers in the matrix of concrete are higher tensile strength compared to organic fibers, cheaper compared to steel fibers, and lack of rust stains at the concrete surface [5]. Glass fibers have many other applications, for instance Glass Fiber Reinforced

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Polymer (GFRP) can be used to enhance the bearing capacity of the pile along with concrete [6]. It can enhance the structural performance of reinforced concrete columns by coating and confine it with a layer of Glass Fibers Reinforced Polyurea (GFRPU) [7]. Due to Glass Fiber Reinforced Concrete (GFRC)'s good mechanical behavior, such as good fire resistance and mold ability, it is appropriate for cladding panels [8]. But using glass fibers in the matrix of concrete also has a disadvantage that all concrete containing glass fibers experience loss of ductility due to accelerated aging [9]. As a result, the new GFRC has higher tensile strength and ductility than aged GFRC. However, both are major drawbacks when considering GFRC as a substance for load-bearing structural parts [10]. To evaluate the long-term performance of GFRC composites, the specimens can be immersed in a hot water bath after curing regime [11]. In this paper, the long-term behavior of GF-UHPC is investigated. By putting the specimens of GF-UHPC in an autoclave and hot water to see how much the mechanical properties of GF-UHPC will be decreased.

A review of relevant papers published in the literature is given next. Rigaud et al. [9] examined the effect of volume percentage of glass fibers on the ductility and bending strength of a thin plate of GF-UHPC. They also evaluated ductility of specimens after wet aging. For this purpose, samples were placed in warm water at 50℃ for 90 days after normal curing. The results showed that ductility was nearly maintained in thin structural elements using an optimum combination of pozzolan in the mixtures. The above-mentioned concrete with 2% volumetric glass fibers absorbs more energy, but it has a lower bending yield stress compared with the specimens with 2.5% volume of fibers.

Yazici et al. [12] investigated the mechanical properties of reactive powder concrete under autoclave curing compared to the regular curing regime. Test results show that autoclave curing is more useful in improving the compressive strength of RPC compared to normal curing, and there is an optimum time, pressure, and temperature for autoclave curing to enhance the mechanical properties of RPC.

Bentur and Diamond [13] investigated the effects of substituting Silica fume with Metakaolin in the UHPC. The results illustrate that this substitution has not a significant impact on the mechanical properties of UHPC. However, Metakaolin is readily available in most countries. Therefore, this ultrafine material has an acceptable price. Moreover, due to its white color, it gives the concrete an esthetic advantage. Krahl et al. [14] investigated the cyclic response of ultra-high performance fibers reinforced concrete (UHPFRC) under cyclic loading test of tension, compression, and bending with 0%, 1%, and 2% steel fibers content. They concluded that an increment in volumetric fibers content could develop residual strength and toughness after cyclic loading.

Madhkhan and Katirai [15] investigated the influence of pozzolanic reactions in GFRC to minimize glass fibers damage with respect to aging. Different pozzolans were separately added to the matrix of GFRC, and the mechanical behavior such as toughness and compressive strength of specimens after 7, 28 and 90 days was tested. The results showed that addition of Nanosilica and Metakaolin could effectively prevent declines in concrete modulus of rupture and toughness with aging. Ali and Qureshi [16] investigated the effect of adding glass fibers to the matrix of concrete made of recycled coarse aggregate. The compressive test showed that glass fibers could compensate to some extent the loss of compressive strength due to substitution of natural aggregate with coarse aggregate. Glass fibers can increase the compressive strength of specimens by about 4-5%, and increase Flexural strength about 50%. Besides, permeability-based durability properties are adversely affected by glass fibers content.

Ryabova et al. [17] investigated long term bending strength of GFRC containing Silica fume and Metakaolin. The result showed that adding Metakaolin in an amount of 30% of Portland cement assist in keeping the long-term strength of FRC and the specific combination of Silica fume and Metakaolin added to the matrix of GFRC can even improve long-term bending strength.

Algburi et al. [18] studied the influence of glass fibers, steel fibers and a combination of both on the mechanical behavior of reactive powder concrete (RPC). Steel fibers improved comprehensive strength, tensile strength, elasticity module, and shear strength of concrete rather than no fibers RPC. However, glass and hybrid fibers increase tensile and shear strength, the comprehensive strength decreased in comparison with no fibers RPC. Liu et al. [19] studied the Mechanical Properties and durability of Glass and Polypropylene Fibers Reinforced Concrete until 28 days. To assess durability, the chloride penetration tests were carried out. The results showed that hybrid fibers reinforced concrete has the best properties rather than two other concrete. Adding polypropylene to the matrix of concrete increases the mechanical properties more than the glass fibers.

Khan et al. [20] studied the effect of substituting some portion of cement with waste glass powder in the matrix of concrete at different curing times. They compared the mechanical properties of substituted concrete with a control sample of concrete at 20MPa compressive strength. The results showed that compressive strength decreased at least 5 percent in compare to normal concrete. However, the Modulus of rupture of the prismatic specimen after 58 days curing in water achieved 2% improvement.

The novelty of this paper is investigating the mechanical behavior of RPC containing glass fibers instead of steel fibers. The effect of steel fibers on the mechanical properties and durability of the ultra-high performance concrete has been extensively investigated. Still a few reports are about GF-UHPC in the literature. Besides, mechanical properties of UHPC reinforced by glass fibers that its silica fume supplanted by Metakaolin were investigated. Also, using glass fibers in UHPC has other advantages compared to steel fibers, such as lower prices and available in the market of Iran.

2. MATERIALS

2. 1. Cement and Pozzolanic Additives

The Portland cement type I produced in the Isfahan factory was used. The chemical composition and physical properties of materials are presented in Tables 1 and 2, respectively.

2. 2. Fine Aggregate

Quartz sand and quartz powder were used as fine aggregates. Quartz powder is used as a filler. The diameter of the grains was between 0.01 and 0.075 millimeters. The characteristics of fine aggregate are shown in Tables 1 and 2. Quartz sand grading is given in Table 3.

TABLE 1. Chemical composition of the materials

Compound (%)	Cement	Silica fume	Metakaolin	Quartz sand
SiO_2	21.68	>91	53	98
Al_2O_3	5.9	0.9	45	1.1
Fe_2O_3	3.2	0.85	0.9	0.4
CaO	63.5	0.95	0.09	0.14
MgO	1.8	0.95	0.03	0
SO_3	1.7	-	-	-
Na_2O	0.2	-	0.1	0.01
K_2O	0.7	-	0.03	0.04
L.O.I	-	2	-	0.15

TABLE 2. Physical properties of materials

Properties	Cement	Silica fume	Metakaolin	Quartz sand
Average particle size (μm)	-	0.23	3	-
Bulk density	-	420	-	-
Specific surface (m^2/g)	0.34	22	23.5	-
Specific gravity (g/cm^3)	3.15	1.9	2.6	2.65

2. 3. Admixtures

The SR340 superplasticizer was used to reduce water requirements. This product is chlorine free and it is produced in accordance with ASTM C-494-15a [21] type B, D, G. The base of this product is the polycarboxylate ether with its molecular side chains. The ratio of the weight of the superplasticizer to cement materials is recommended to be 0.2-1.5%. The superplasticizer density is 1.09 g/cm^3 [22].

2. 4. Fibers

Glass fibers is a material made up of large thin fibers of glass. Glass fibers with the specifications given in Table 4 has been used. Glass fibers content was 1.5 and 2% by total volume. Due to the low workability of fresh concrete, the highest fibers content was 2.2% of concrete volume.

3. MIXTURE DETAILS

Mixed designs are obtained in the absolute volume method with an air content of 2%. Other weight parameters of the mixtures were constant (water/binder=0.2, Silica fume or Metakaolin/cement=0.3, quartz powder/cement=0.32 and quartz sand/cement=1.5) [23]. Abbreviations were used for mixtures according to usage of Silica fume or Metakaolin and glass fibers content. Three mixtures containing Silica fume were made:

- Without glass fibers (S0)
- With 1.5% volume glass fibers (S1.5)
- With 2.2% volume glass fibers (S2.2).

TABLE 3. Grading of quartz sand

Mesh size(#)	30	50	80	100	120	140	170
Sieve size(mm)	0.6	0.3	0.18	0.15	0.125	0.106	0.09
Retained(g)	0	226.1	217.8	250.8	190	100.1	15.3
Cumulative retained(g)	0	226.1	443.9	694.7	874.7	984.8	1000.1
Retained(%)	0	22.61	21.78	25.08	19	10.01	1.53
Cumulative retained (%)	0	22.61	44.39	69.47	87.47	98.48	100.01
Sand passing through	100	77.39	55.61	30.53	11.53	1.52	0

TABLE 4. Physical properties of glass fibers [24]

Type	Density (g/cm^3)	Length (mm)	ZrO_2	Failure strain	Young's modulus (MPa)	Tensile strength (MPa)
AR-Glass	2.74	10	20%	2%	74000	1480

Three reference mixtures containing Metakaolin were made:
- Without glass fibers (M0)
- With 1.5% volume glass fibers (M1.5)
- With 2.2% volume glass fibers (M2.2).

The mixture details are given in Table 5.

4. EXPERIMENTAL PROCEDURE

4. 1. Fabrication of UHPC

All of the UHPCs were mixed and prepared using a mortar mixer with a nominal capacity of 10 liters. The mixer has a rotational speed of 75 rpm (round per minute) with an effective capacity of 5 liters. The mixing sequence was: dry powders included quartz sand, quartz powder, cement, and pozzolan were poured into the mixer in that order, and the mixing continues for 8 minutes or more.

While the mixer is working, half of the water is poured into the mixer; then the mixing continues for 2 minutes. Next, the water and the superplasticizer are added, and mixing continues for 3 minutes. Residual superplasticizer is added to the compound, followed by adding glass fibers and mixing at high speed for 5 minutes. It should be mentioned that a portion of the mortar was used for the ASTM C1437-13 [23] test was used to determine the flow of mortars containing cementitious materials before adding the fibers.

4. 2. Manufacturing of the Specimens

The UHPC was made in cube mortar molds (75×75×75mm) and prismatic specimens (350×50×13.5mm), compacted by hand and using a vibrating table. The samples were kept in the molds for 48 hours at room temperature at about 20°C. The surface of the samples was covered with wet fabric to prevent moisture loss and surface cracking. After this period, the specimens were detached from the steel molds. The first group of samples was put in water at 20 °C for 28 days, the second group was autoclaved under (121°C, 1.25 MPa) for 24 hours, and the third group was autoclaved then kept in hot water at 50°C for 50 days.

4. 3. Mechanical Properties

The mechanical behavior of the UHPC was studied by compressive and flexural strength of samples. Cube specimens were used to determine the compressive strength. This test was performed according to BS EN1881-116 [25]. For determining the flexural strength, the prismatic specimens were utilized. The flexural strength test was performed according to ASTM C78-10 [26]. The specimens were loaded at the mid-span point, as shown in Figure 1-a. The distance between simple supports was 300 mm, and electronic transducers were used to measure mid-span deflection (δ).

Furthermore, ASTM C1018-97 [27] was used for determining toughness parameters of fiber-reinforced concrete in accordance with Figure 1-b.

Toughness indices I5, I10, I20 show the flexural strength and ductility of the specimen. Calculation of the toughness indices is shown in Figure 1-b, and Equations 1 to 3. These indices show the ratio of the specific area beneath the load-deflection curve to the area under the first-crack deflection (δ).

$$I_5 = \frac{Area_{O'ACD}}{Area_{O'AB}} \quad (1)$$

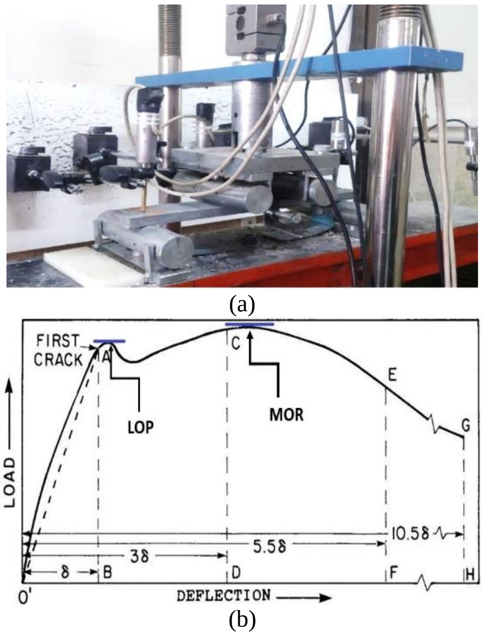
$$I_{10} = \frac{Area_{O'AEF}}{Area_{O'AB}} \quad (2)$$

$$I_{20} = \frac{Area_{O'AGH}}{Area_{O'AB}} \quad (3)$$

In Equations (1), (2), and (3), $Area_{O'ACD}$, $Area_{O'AEF}$, $Area_{O'AGH}$ and $Area_{O'AB}$ are the areas under the load-deflection curve shown in Figure 1-b.

TABLE 5. Proportions of the concrete mixtures (kg/m^3)

Materials (kg/m^3)	UHPC with Silica fume			UHPC with Metakaolin		
	S0	S1.5	S2.2	M0	M1.5	M2.2
Cement	683.9	670.12	665.26	701.8	687.57	681.43
Silica fume	205.2	201	199.58	0	0	0
Metakaolin	0	0	0	210.5	206.27	204.4
Quartz powder	218.8	214.44	212.88	224.6	220	218
Quartz sand	1025.9	1005.18	997.9	1052.7	1031	1022
Super plasticizer	8	13.07	12.97	12.77	17.9	19.5
Water	177	174.23	172.97	182.5	178.8	177
Glass fibers	0	41.1	60.28	0	41.1	60.28
Super plasticizer/binder	0.9%	1.5%	1.5%	1.4%	2%	2.2%



(a)

(b)

Figure 1. (a) Four-point Flexural strength test, (b) Characteristics of the load-deflection curve ASTM C1018-97 [27]

The residual strength factors $R_{5,10}$ and $R_{10,20}$ are the strength retained after the first crack. These factors are calculated by Equations (4) and (5).

$$R_{5,10} = 20(I_{10} - I_5) \tag{4}$$

$$R_{10,20} = 10(I_{20} - I_{10}) \tag{5}$$

5. EXPERIMENTAL RESULTS

Adding glass fibers in the concrete matrix plays two major roles in the mechanical properties of concrete. First, the main role is to increase the energy absorbing capacity and improve crack resistance [28]. Second, based on the experimental study, it is concluded that addition of excessive amounts of glass fibers in concrete reduces the mechanical strength. High volume of glass fibers can result in deterioration of concrete homogeneity and increases the probability of weak areas occurring in the concrete matrix [29].

Accelerated aging is defined as accelerating the formation of the hydration products, which improves the concrete strength, can affect the first role of fibers in the matrix of concrete. The chemical reactions between hydration products and pozzolans produce pozzolanic C-S-H gel, which improves the mechanical properties of concrete. Nevertheless, the interaction of hydration products, mainly calcium hydroxide, with glass fibers can have harm impact on the long-term behavior of the GFRC. Hydration products gradually bond the filaments together, which makes fibers brittle, and reducing the strain and strength capacity of the composite [30]. These effects will be used later to justify obtained results. In the next `compressive and flexural strength of specimens are presented and discussed.

5. 1. Flowability of Mortars

To determine the flowability of the mortar of UHPC, ASTM C1437-13 [23] standard method was used. The results are presented in Table 6. It should be noted that in all mix designs, the water to cement ratio was 0.2.

Owing to the high binder volume and low water/binder ratio, the mixture has low workability; therefore, it needs a high amount of superplasticizer. The water/binder ratio is constant, but the superplasticizer/binder ratio may vary to keep the workability of mix designs approximately similar. Mix designs incorporating silica fume have higher flow than mix designs containing Metakaolin. In the mixtures containing fibers, the amount of superplasticizer is higher than the mixtures without fibers, because the glass fibers inhibit the flow of mortars.

5. 2. Compressive Strength

The results of compressive strength for mix designs are shown in Figure 2. Under accelerated aging, each test was repeated six times, and for normal and autoclave curing methods, each test was repeated three times. The first notable result is that adding glass fibers results in higher compressive strength only in normal curing, but after autoclave curing and placing specimens in hot water (accelerated aging), specimens with lower glass fibers attain higher compressive strength.

In the next section, the effect of curing method, accelerated aging, and addition of Metakaolin are investigated.

5. 2. 1. Comparison of Normal and Autoclave Curing

The compressive strength of UHPC without fibers after autoclave curing was 20 % higher than standard curing specimens, which is probably due to the accelerated rate of the hydration process and pozzolanic reaction. However, the compressive strength of specimens containing glass fibers is almost the same as or even less than strength of specimens with 2.2% (volumetric) fibers. It can be inferred that the glass fibers deteriorate the concrete homogeneity and this effect is stronger than preventing crack propagation; because

TABLE 6. Flowability of mortars

Mixtures	S0	S1.5	S2.2	M0	M1.5	M2.2
Superplasticizer/ binder	0.90%	1.50%	1.50%	1.40%	2%	2.20%
Diameter(mm)	150	185	195	155	180	195

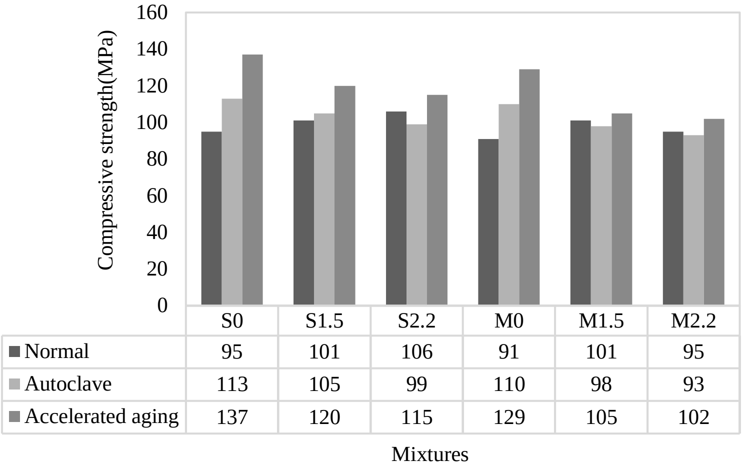


Figure 2. Compressive strength of samples after curing and thermal treatment

hydration products affect the performance of glass fibers and reduce filament pull-out. As a result, the composite cured by autoclave becomes more brittle than ordinary curing.

5. 2. 2. Effect of Accelerated Aging

All specimens experienced a remarkable increase in the compressive strength after accelerated aging compared with normal or autoclave curing; but specimens subject to compressive strength test fail more abruptly and explosively, particularly specimens without fibers. Hence, the specimens become more brittle. Although increasing hydration products weakens the glass fibers in the concrete matrix, the compressive strength of specimens under accelerated aging is improved. The formation of the hydration products especially C-S-H gel strengthens the concrete matrix. Therefore, after accelerated aging which increases the age of the concrete containing glass fibers, not only depressed the strength, but also the strength has been improved.

5. 2. 3. Effect of the Metakaolin

Substitution of silica fume by Metakaolin led to a small decrease in compressive strength. After accelerated aging, an increase in compressive strength for specimens containing SF and MK was 16 and 11% on average. This shows that pozzolanic activity in silica fume is more complete compared to Metakaolin, and the silica fume gives a higher compressive strength in this case.

5. 3. Flexural Strength

Prismatic specimens were subjected to curing or accelerating aging and then used for bending tests. Each test was repeated six times and the results (average of six tests) are presented in Tables 7 and 8. UHPC has a mean modulus of rupture (MOR) of 8.8 MPa at 28 days, and GF-UHPC has MOR 11- 14 MPa depending on fiber content. Fibers play a pivotal role in increasing ductility and flexural strength. As an example, after normal curing, The MOR of S1.5 is 18.92% higher than S0. In addition, fibers inhibit abrupt failure and control the width of

TABLE 7. Results of flexural strength test for Silica fume mixtures

Mixtures		**S0**			**S1.5**			**S2.2**		
Curing type		**Normal curing**	**Autoclave curing**	**Accelerated aging**	**Normal curing**	**Autoclave curing**	**Accelerated aging**	**Normal curing**	**Autoclave curing**	**Accelerated aging**
Limit of proportionality (MPa)		8.72	9	8.11	10.37	12.25	8.25	11.54	11	6.54
Modulus of rupture (MPa)		8.72	9	8.11	11.2	14	8.7	14.05	12.4	6.91
Index value	I_5	1	1	1	4.71	5.48	4.1	5.22	5.1	4.3
	I_{10}	1	1	1	7.22	6.68	4.6	7.57	6.37	4.87
	I_{20}	1	1	1	8.72	6.68	4.6	8.62	6.39	4.87
Residual strength factor (%)	$R_{5,10}$	0	0	0	50.23	24	10	47	25.4	11.4
	$R_{10,20}$	0	0	0	15	0	0	10.5	0.2	0

TABLE 8. Results of flexural strength test for Metakaolin mixtures

Mixtures		**M0**			**M1.5**			**M2.2**		
Curing type		**Normal curing**	**Autoclave curing**	**Accelerated aging**	**Normal curing**	**Autoclave curing**	**Accelerated aging**	**Normal curing**	**Autoclave curing**	**Accelerated aging**
Limit of proportionality (MPa)		9	11.6	10.3	10.15	13.5	8.85	10.1	11.85	7.33
Modulus of rupture (MPa)		9	11.6	10.3	12.5	14.3	9	12.8	12.8	7.8
Index value	I_5	1	1	1	5.1	4.78	3.98	5.17	5.2	4.38
	I_{10}	1	1	1	7.75	6.13	4.54	7.5	6.77	5.19
	I_{20}	1	1	1	8.99	6.13	4.54	9.1	6.77	5.19
Residual strength factor (%)	$R_{5,10}$	0	0	0	55	27	11.2	46.6	31.4	16.25
	$R_{10,20}$	0	0	0	11.46	0	0	16	0	0

cracks, therefore, the concrete has the ability to withstand more load. As a result, index values of specimens containing fibers are more than 1 and without fibers are 1, meaning that they will collapse after first crack.

Adding glass fibers to the flexural specimens increased modulus of rupture and toughness after normal curing. However, after accelerated aging and autoclave curing, MOR of specimens containing 1.5% fibers content was higher than 2.2% fibers content because the hydration products reduced filament pull-out and made them brittle. Hence, fibers' role in the deterioration of concrete homogeneity overcame the role of improving crack resistance.

Load-deflection diagrams after normal and autoclave curing are shown in Figures 3-6 shows the effect of the curing regime and percentage of glass fibers on the flexural strength better than Table 7. To be able to compare load-deflection diagrams, specimens should have the same thickness. As a result, we tried to keep the thickness and width of specimens constant, but because of low workability, the thickness of specimens was variable between 13mm to 15mm.

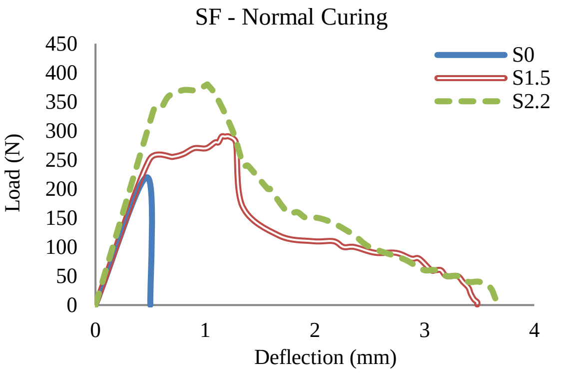


Figure 3. Load-deflection curves of SF specimens after normal curing

5. 3. 1. Comparison of Normal and Autoclave Curing

Autoclave curing has consequential impacts on the properties of cement-based materials. High temperatures intensify the rate of reactions and can improve some characteristics of the specimens. Besides, the combination of pressure and high temperatures can change the chemistry of hydration products [12].

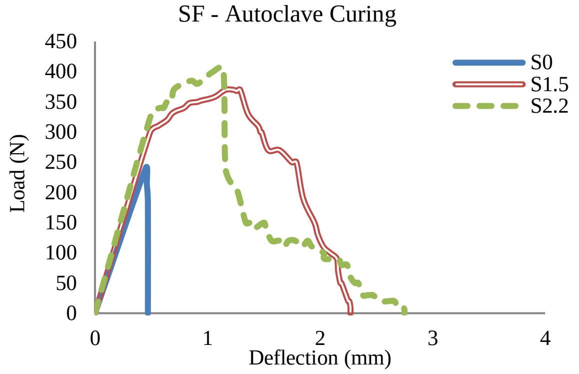


Figure 4. Load-deflection curves of SF specimens after autoclave curing

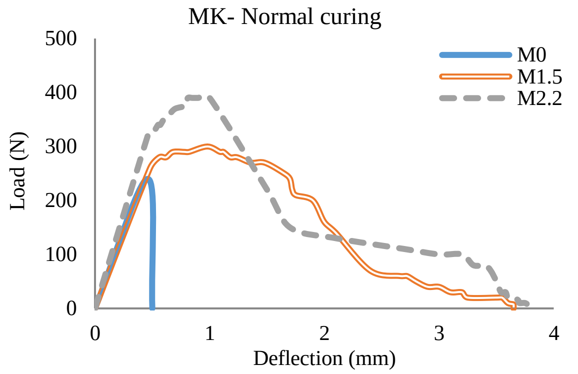


Figure 5. Load-deflection curves of MK specimens after normal curing

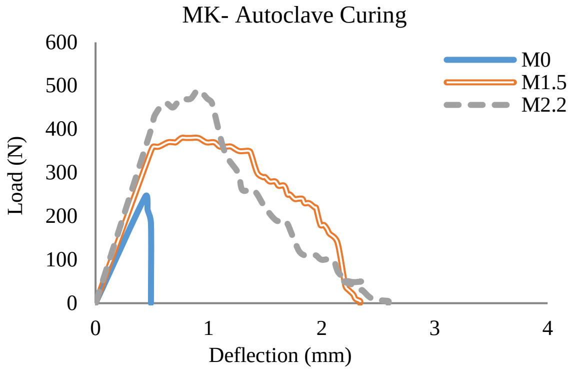


Figure 6. Load-deflection curves of MK specimens after autoclave curing

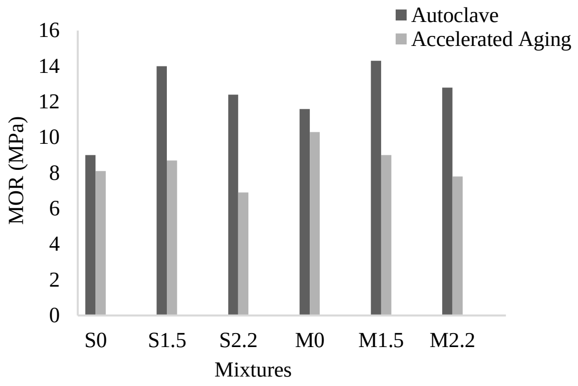


Figure 8. MOR of specimens after autoclave curing and accelerated aging

Autoclave curing increases MOR and LOP (Limit of Proportionality). However, final mid-span deflection, residual strength factor R5,10, and I10 index value decrease showing loss of ductility of specimens. High temperatures can augment porosity and deteriorate the fiber–matrix and aggregate–matrix bond. As a result, after autoclave curing, the behavior of concrete with fibers may become more brittle. Based on Figure 7, the loss of R5,10 is 40% for GF-UHPC. In other words, specimens with normal curing have more residual strength after the first crack, and they sustain more deformation and absorb more energy. After autoclave curing, specimens containing MK have a slightly higher residual strength or energy absorption than SF.

5. 3. 2. Effect of Accelerated Aging

Accelerated aging can simulate the natural weathering phenomenon due to the development of hydration products that make glass fibers brittle material [9]. For this purpose, after autoclave curing, specimens were placed in hot water at 50℃ for 50 days. Placement in the hot water led to a significant reduction of flexural strength for all specimens. In Figure 8, the MOR of specimens after autoclave curing and accelerated aging are shown.

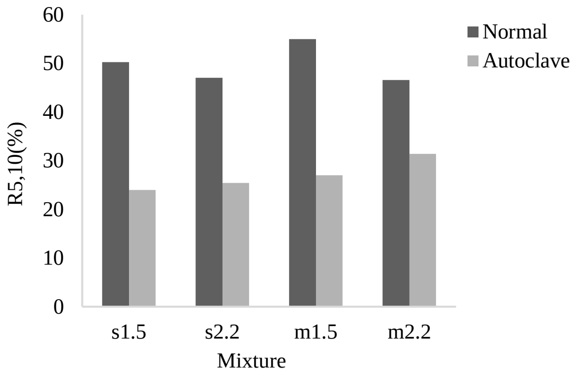


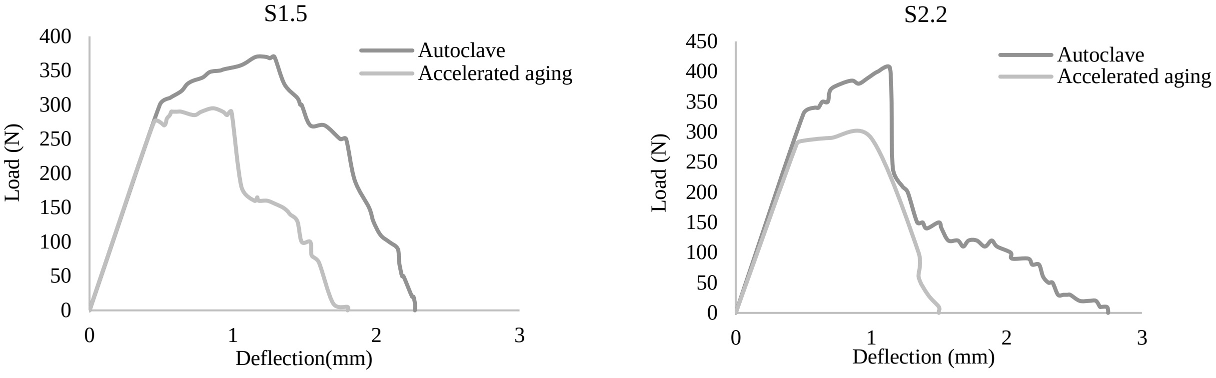
Figure 7. Residual strength factor R5,10 after normal and autoclave curing

Specimens with and without fibers lost 40% and 10% of MOR after accelerated aging. For specimens containing fibers, this can be explained by producing more hydration products, especially calcium hydroxide. They surround the thin fiber threads and connect them, and therefore the tensile strength of the fibers is reduced. In this situation, the load bearing capacity of the specimens is reduced, and the specimens show more brittle behavior.

In the specimens without fibers, the advancement of pozzolanic reaction gives us the expectation that the modulus of rupture will not drop. But the rupture modulus drop can be because of thermal treatment of UHPC, which is a complicated process. The thermal treatment improves pozzolanic reactions with cement hydration products. These chemical reactions are beneficial to some extent and if this process continues for more time, it can deteriorate the mechanical properties of concrete [1]. The loss of MOR after accelerated aging in GF-UHPC and GFRC are nearly similar. For instance, Jones et al. [31] reported that after accelerated aging of GFRC in 50°C water for 50 days, MOR was reduced by 34%. Bentur and Diamond [13] reported that after placing GFRC in 50°C water for 28 days, MOR decreased by 60%. Marikunte et al. [11] said after placing GFRC in 50°C water for 84 days, MOR was reduced by 50%.

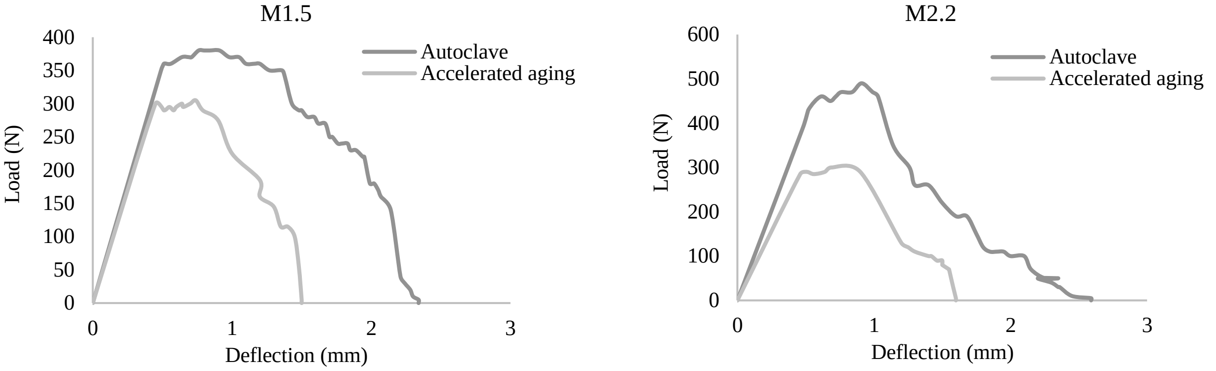
The load-deflection diagrams in Figures 9 and 10 show the effect of accelerated aging clearly. These figures show a reduction in flexural strength, and both load capacity and mid-span deflection are diminished.

Due to the variable thickness of the specimens, for a better comparison of mixtures, index values and residual strengths are shown in Figures 11 and 12, respectively.



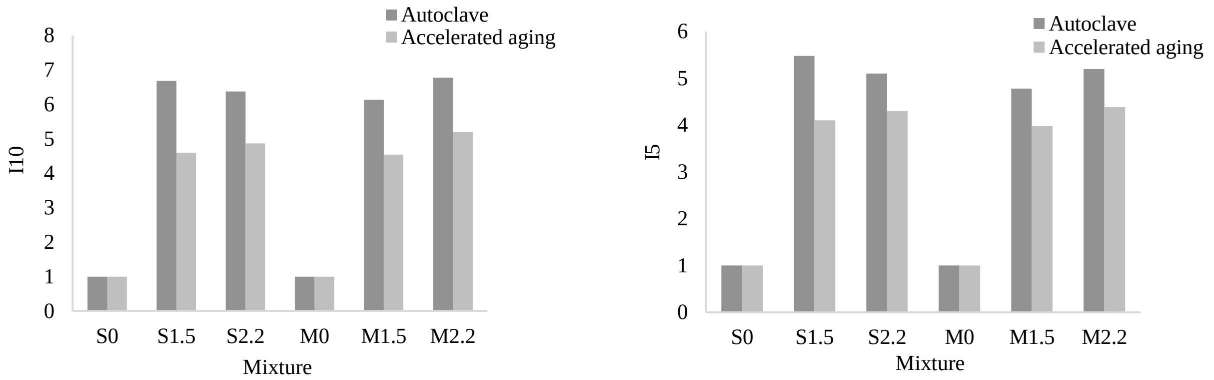
(a) (b)

Figure 9. Load-deflection diagrams of specimens with SF, (a) containing 1.5% fiber and (b) containing 2.2%



(a) (b)

Figure 10. Load-deflection diagrams of specimens with MK, (a) containing 1.5% fiber and (b) containing 2.2%



(a) (b)

Figure 11. Index values after accelerated aging, (a) index I10 and (b) index I5

Figure 11 illustrates the loss of toughness. The toughness indices of all specimens decreased as a result. The index I10 has a more severe reduction than index I5, which shows that the specimens have less deformation. Substitution of SF by MK leads to a small increase in toughness. Index values of specimens contain MK have a lower reduction after accelerated aging, particularly for M1.5. After accelerated aging, R5,10 is decreased by about 55% in all specimens.

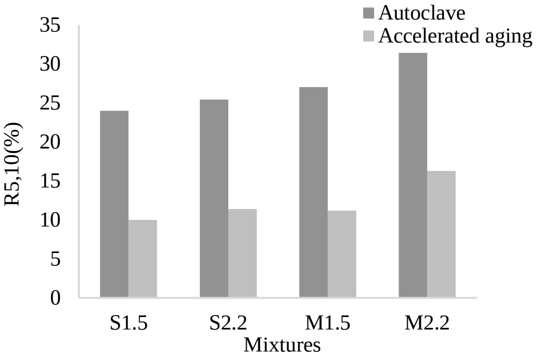


Figure 12. Residual strength factor R5, 10 after accelerated aging

6. CONCLUSIONS

In this research, the attempt is to assess the mechanical properties of Ultra-High Performance Concrete reinforced by glass fibers. The effect of using glass fibers in the matrix of UHPC is investigated with three types of curing regimes (Normal, Accelerated aging and Autoclave) and two types of pozzolans (silica fume and Metakaolin). The following results have been obtained.

Using glass fibers in the flexural specimens of UHPC highly increases the toughness and modulus of rupture.

The autoclave curing increased the limit of proportionality and modulus of proportionality compared to the normal curing; however, the specimens' toughness decreased.

After accelerated aging with hot water, which models the behavior of glass fibers reinforced concrete over long periods, the compressive strength of GF-UHPC specimens has risen. Therefore, there is no concern about losing the compressive strength of GF-UHPC by passing the time. In addition, modulus of rupture of all flexural specimens has been reduced. The decrease of the modulus of rupture in samples that contain glass fibers is about 40% compared to the autoclave curing. Also, the residual strength factor is dropped at least 48% rather than normal curing.

Substitution of silica fume with Metakoline has a positive effect on keeping resilience under accelerated aging. Using Metakaolin causes lower flowability of fresh concrete.

The finding of this research was to emphasize on the ability of substitution of glass fibers with steel ones in UHPC and to present their mechanical properties. Another research will be the study of the durability of GF-UHPC under freeze and thaw cycles, impermeability and so on.

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Persian Abstract

چکیده

بتن فوق توانمند ماده‌ای متشکل از سیمان و ریزدانه است که ساختاری یکپارچه و دارای مقاومت فشاری و دوام بالایی در برابر شرایط محیطی شدید می‌باشد. استفاده از الیاف فلزی کوتاه در این بتن رایج است؛ زیرا باعث افزایش مقاومت خمشی، دوام و شکل‌پذیری این بتن می‌شود. استفاده از الیاف شیشه در این نوع بتن تکنیک جدیدی است و مزیت آن نسبت به الیاف فولادی، سبک بودن و ارزان بودن الیاف شیشه نسبت به الیاف فولادی می‌باشد. همچنین بتن مسلح شده با الیاف شیشه را می‌توان درصفحات نازک برای زیبایی و نمای سازه بکار برد. با این وجود، الیاف شیشه سازگار با فرآیند هیدراسیون در محیط قلیایی بتن نیستند و با گذر زمان، دچار آسیب می‌شوند. بنابراین با کامل شدن فرآیند هیدراسیون و گذر زمان، مقاومت مکانیکی بتن حاوی الیاف شیشه کاهش می‌یابد. برای شبیه‌سازی رفتار بلند مدت و افزایش فرآیند هیدراسیون این نوع بتن، مقاومت مکانیکی نمونه‌ها بعد از عمل‌آوری‌های معمولی، استفاده از اتوکلاو و سپس قرار گرفتن در آب گرم ۵۰ درجه سانتیگراد به مدت ۵۰ روز بررسی شدند. نتایج نشان داد بعد از عمل‌آوری‌های حرارتی، شاخص‌های شکل‌پذیری و مقاومت خمشی نمونه‌های خمشی کاهش چشمگیری می‌یابد. برای مثال، نمونه‌های قرارگرفته در آب گرم حدود ۴۰٪ مدول گسیختگی کمتر نسبت به حالت بعد از عمل‌آوری با اتوکلاو دارند؛ اگرچه مقاومت فشاری نمونه‌های فشاری حداقل به میزان ۴٪ نسبت به حالت بعد از عمل‌آوری معمولی افزایش یافته است. همچنین اثر جایگزینی متاکائولین به جای میکروسیلیس درساختار بتن جهت مطالعه رفتار بلند مدت بتن فوق توانمند بررسی شد. استفاده از متاکائولین شکل‌پذیری نمونه‌های خمشی را به مقدار کم بهبود می‌بخشد.