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Effect of Steel Fiber Volume Fraction on the Mechanical Behavior of Ultra-high Performance Concrete Composites

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ABSTRACT

In order to investigate the effect of fiber volume fraction on the mechanical behavior of ultra-high performance concrete composites (UHPCC), five different volume fractions of macro steel fibers (V_f = 0.5, 1, 1.5, 2 and 2.5%) are used within identical mortar matrix. Ultra-high performance fiber reinforced concrete (UHPFRC) mix was designed to achieve a compressive strength of 155 MPa based on the particle packing method. For 12 series of UHPCC mixes, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity at 28 days are determined. Test results showed a significant improvement in splitting tensile and flexural strengths of UHPFRC with the addition of steel fibers. The maximum values of compressive, splitting tensile and flexural strengths were 155.39, 17.76, and 32.50 MPa, respectively. Stress-strain behavior of fiber-reinforced concrete composites is studied and elastic modulus values evaluated are in the range of 39.52-47.99 GPa. Empirical expressions are developed based on the test results in terms of fiber volume fraction to predict the 28-day strengths of UHPFRC. Comparing the experimental values of earlier researchers to the ones predicted by empirical equations, the average absolute error (AAE) value obtained is within 5%. The proposed model's predictions are in good agreement with the experimental values. Relationship between compressive and flexure strengths of UHPFRC isdeveloped with R^2=0.99 and validated.

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NOMENCLATURE

UHPCC	Ultra-high performance concrete composites	f_c	Compressive strength of UHPCC
UHPFRC	Ultra-high performance fiber reinforced concrete	f_{cf}	Compressive strength of UHPFRC
QP	Quartz powder	f_{sp}	splitting tensile strength of UHPCC
GGBS	Ground grannulated blast furnace slag	f_{spf}	splitting tensile strength of UHPFRC
kN	Kilo Newton	f_r	flexural strength of UHPCC
MPa	Megapascal	f_{rf}	flexural strength of UHPFRC
GPa	Gigapascal	E_c	modulus of elasticity of UHPCC
V_f	Fiber volume-fraction	E_{cf}	modulus of elasticity of UHPFRC

1. INTRODUCTION

Ultra-high performance concrete (UHPC) is a brittle material. In order to overcome this property micro/macro steel fibers are incorporated in to the concrete matrix [1-3]. Since many years researchers have been studying and trying to improve the tensile properties of UHPFRC in terms of flexural strength and bending capacity [4-5]. Steel fibers in the concrete matrix improve the mechanical properties, ductility, toughness and impact strength [6-8]. Mostly, fiber parameters like quantity, shape, and orientation determine the tensile performance of UHPFRC [9-11]. UHPFRC is commonly developed using steel fibers having a diameter of 0.20 mm and a length of 13 mm [12-14]. A steel fiber volume fraction of 2 % is often used to develop an economical and workable UHPFRC [15-16].

The effect of steel fiber-volume fraction (V_f = 1, 2, 3 and 4%) in UHPFRC was studied by Yoo et al. [17] and found that the best results were observed in the concrete

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mixture with V_f = 3% in terms of interfacial bond strength, mechanical and shrinkage behaviors. Three different steel fiber lengths (8, 12 and 16mm) and volume fractions (V_f = 1, 3 and 6%) were used by Abbas et al. [18] for his investigations on UHPFRC mixtures. The results showed an improvement in the mechanical properties of the UHPFRC mixtures with increment in steel fiber volume fraction. It was also observed that UHPFRC mixtures having short steel fibers had better flexural performance when compared with concrete mixtures having a similar volume of long steel fibers. Yu et al. [19] found that the inclusion of steel fibers controlled flexural toughness when the mechanical properties and flexural toughness were investigated for the UHPFRC which was developed with a low binder content. A 5% enhancement in compressive strength was observed by Tsioulou et al. [20] in a UHPFRC mixture containing a 3% steel fiber-volume fraction when compared to plain UHPC as he investigated the addition of different steel fiber volume fractions (V_f = 0, 1, and 3%) in UHPFRC.

To achieve the needed strengths and material properties, variable steel fiber volume fractions, widely ranging from (V_f = 0-6%) were used in different studies to develop UHPFRC. The most convincing technique to improve the tensile performance of UHPCC is by increasing the steel fiber volume fraction [21-23]. Moreover, the literature showslimited use of macro steel fibers when compared to micro and short steel fibers in the development of UHPFRC [29-31]. In this context, the present study gains prominence as macro and long steel fibers are used to develop UHPFRC and therefore to study their effect on mechanical properties and elastic modulus.

2. EXPERIMENTAL PROGRAM

2. 1. Materials and Mix Proportions

The mix proportion of UHPFRC with w/c ratio of 0.25, used in this study is presented in Table 1. The chemical compositions of Ordinary Portland cement (OPC) of 53-Grade, Alccofine 1203, Quartz powder, and Ground granulated blast furnace slag (GGBS) are listed in Table 2 and these were used as cementitious materials. Locally available river sand confirming to IS 383 (1970) was used as fine aggregate.. For adequate workability of UHPFRC, poly carboxylate ether (PCE) based super plasticizer (SP) was added. For investigating the effect of fiber volume fraction on mechanical properties of UHPFRC, the crimped macro steel fibers with an aspect ratio of 70 and having dimensions of 35 mm length and a diameter of 0.5 mm were used with UHPCC at V_f = 0.5, 1, 1.5, 2 and 2.5%. In this study, two mixes of UHPFRC were developed with varying fiber volume fraction. Mix designations from UHPCC-AQ to UHPFRC-AQ 2.5, UHPFRC is designed with alccofine and quartz powder and mix designations from UHPCC-AG to UHPFRC-AG 2.5, UHPFRC is designed with alccofine and GGBS [24-25]. The number denotes fiber volume fraction in percentage. All the cast specimens were cured at room temperature and tested at 28 days.

2. 2. Test setup and Procedure

2. 2. 1. Compression Test

Compressive strength tests were conducted on 100 x 100 x 100 mm^3 cube specimens according to IS 516-2004. The tests were carried out on a servo-controlled compression testing machine (CTM) having a maximum load capacity of 2000 kN, and the load was applied at a rate of 14 MPa/min. To calculate the average compressive strength, a minimum of three specimens were tested.

2. 2. 2. Splitting Tensile Test

On a 2000 kN capacity CTM, a cylindrical specimen with dimensions 100 mm dia. and 200 mm height was used for splitting tensile strength testing according to ASTM C 496-1996.

2. 2. 3. Flexure Test

According to ASTM C78-1994 [26], flexural strength tests were performed on 100

TABLE 1. Mix Proportion of UHPCC

Material	UHPFRC-AQ	UHPFRC-AG
Cement	1	1
Alccofine	0.25	0.25
Quartz Powder	0.3	-
GGBS	-	0.3
Fine Aggregate	1.2	1.2
w/c	0.25	0.25
SP (%)	2	2
Steel fiber, V_f (%)	0-2.5	0-2.5

TABLE 2. Chemical Composition of Cementitious Materials

Compound (%)	Cement	Alccofine	Quartz Powder	GGBS
SiO_2	18.91	34.83	99.5	33.45
Al_2O_3	4.51	21.44	0.08	13.46
Fe_2O_3	4.94	1.39	0.04	0.31
CaO	66.67	33.91	0.01	41.7
MgO	0.87	6.81	0.01	5.99
SO_3	2.5	0.010	0.01	2.74
K_2O	0.43	-	0.01	0.29
Na_2O	0.12	-	0.01	0.16
LOI	1.7	1.42	0.28	0.26

x 100 x 500 mm^3 prismsunder third point loading with a simply supported span of 400 mm on a hydraulically controlled closed loop universal testing machine (UTM) of capacity 1000 kN.

The tests were carried out at a rate of 0.1 mm/min of deformation.

2. 2. 4. Modulus of Elasticity A cylindrical specimen having dimensions of 150 mm dia. and 300 mm height isused for the uniaxial compression test according to ASTM C 39-1992 [27] in a CTM with a maximum load capacity of 3000 kN.

3. RESULTS AND DISCUSSIONS

3. 1. Compressive Strength Compressive strength (f_{cf}) values of 12 UHPFRC mixtures are listed in Table 3 according to their fiber volume fractions. Figure 1 illustrates the graphical representation of compressive strength values. To calculate the compressive strength, an average of at least three tested specimens was taken. From both Figure 1 and Table 3, it can be observed that the addition of steel fibers to UHPCC improved the compressive strength of concrete mixes. A gradual increase in compressive strength was observed with the increment in steel fiber volume fraction of up to 2%. However, the UHPFRC mixtures containing 2.5% steel fibers had a minimum impact with a negligible increment in compressive strength. The improvement of compressive strength with steel fiber addition can be attributed to the ability of fibers to hold the concrete matrix together and delay the micro-crack formation. And beyond 2%, higher fiber content resulted in negligible improvement due to the inhomogeneous distribution of fibers in the concrete mixture.

A maximum compressive strength of 155.39 MPa was attained by the UHPFRC-AG 2.5 mixture, which is around 13.7% higher than the unreinforced UHPCC-AG. In a comparison of the two UHPFRC mixtures, UHPFRC-AG yielded higher compressive strength values than UHPFRC-AQ at all fiber volume fractions. The addition of long macro steel fibers to UHPCC has an overall moderate improvement in compressive strength, as the literature suggests an increment of around 30% with the addition of short, micro steel fibers [18]. The other reason for moderate improvement could be due to the fact that the improvement in compressive strength is high when the UHPFRC mixtures containing a high volume of steel fibers are temperature cured. All the tested cube specimens exhibited brittle failure. The unreinforced UHPCC specimens collapsed with rapid and explosive failures, whereas the fiber reinforced UHPFRC specimens collapsed gradually without considerable fragmentation. The failure pattern of UHPFRC cube specimen under compressive loading is shown in Figure 2(a).

The compressive strength values of UHPFRC mixtures can be expressed as a function of fiber volume fraction (V_f) using the linear regression analysis on experimental results presented in Table 3, and the expressions are as follows:

$$f_{cf} = f_c + 6.58\,(v_f) \quad \text{for UHPFRC-AQ} \tag{1}$$

$$f_{cf} = f_c + 7.52\,(v_f) \quad \text{for UHPFRC-AG} \tag{2}$$

TABLE 3. 28-Day Compressive, Splitting tensile and Flexural Strength Properties of UHPFRC and their Improvements

Mix ID	Fiber Volume Fraction (v_f) (%)	28 days Compressive strength (MPa)	Improvement in Strength (%)	28 days Splitting tensile strength (MPa)	Improvement in Strength (%)	28 days Flexural Strength (MPa)	Improvement in Strength (%)
UHPCC-AQ	0	132.57	0.00	10.35	0.00	17.46	0.00
UHPFRC-AQ 0.5	0.5	137.61	3.80	11.85	14.50	20.62	18.10
UHPFRC-AQ 1	1	141.32	6.60	13.07	26.30	23.69	35.70
UHPFRC-AQ 1.5	1.5	144.50	9.00	13.95	34.80	26.09	49.40
UHPFRC-AQ 2	2	147.55	11.30	14.70	42.00	27.64	58.30
UHPFRC-AQ 2.5	2.5	149.01	12.40	15.08	45.70	28.44	62.90
UHPCC-AG	0	136.67	0.00	11.73	0.00	19.24	0.00
UHPFRC-AG 0.5	0.5	142.00	3.90	13.56	15.60	22.93	19.20
UHPFRC-AG 1	1	146.24	7.00	15.19	29.50	26.19	36.10
UHPFRC-AG 1.5	1.5	149.93	9.70	16.29	38.90	28.98	50.60
UHPFRC-AG 2	2	153.48	12.30	17.25	47.10	31.30	62.70
UHPFRC-AG 2.5	2.5	155.39	13.70	17.76	51.40	32.50	68.90

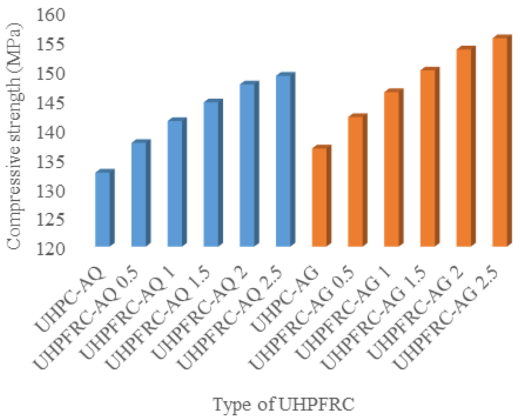
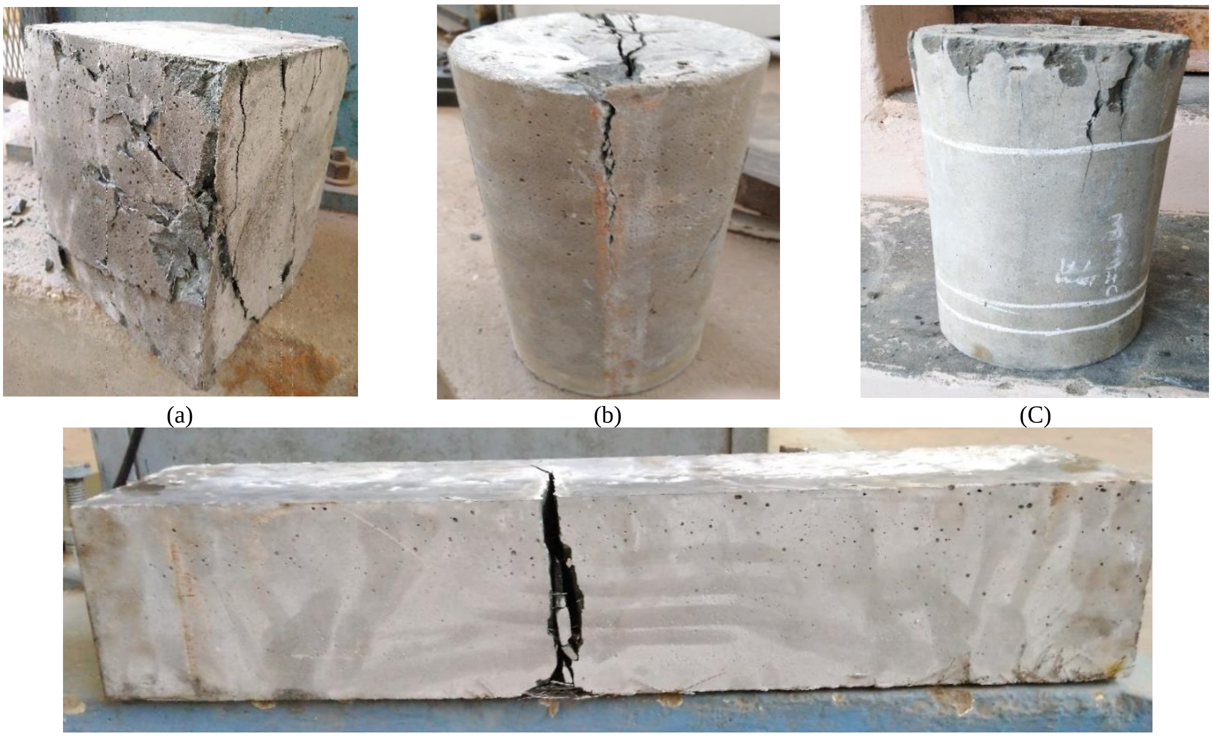


Figure 1. Compressive strength development of various UHPFRC mixes with varying fiber volume fraction (V_f)

The empirical equations developed by using linear regression analysis on experimental values is used to predict the compressive strength values of UHPFRC mixtures and are presented in Table 4. The experimental values of earlier researchers were compared with the values predicted by developed empirical equations, and the average absolute error (AAE) obtained was within 5%. Figure 3 shows the comparison of experimental values of compressive strength (MPa) of UHPFRC with the predicted values by the model. It isfound that the predictions obtained by the proposed model arein good agreement with experimental values.


(a) (b) (C)

(d)

Figure 2. Failure patterns of UHPFRC specimens under (a) Compressive load, (b) Splitting tensile load, (c) Uni-axial compression load, and (d) Flexural load

3. 2. Splitting-tensile Strength

The addition of steel fibers resulted in a significant improvement in the tensile properties of UHPFRC. Table 3 presents the splitting tensile strength values of UHPFRC mixtures along with the percentage improvement with the addition of steel fibers. A splitting tensile strength of 10.35 MPa was obtained by the UHPCC-AQ mixture having zero fiber content, which increased by 45.7% to 15.08 MPa. This shows the significance of steel fiber incorporation in UHPFRC to obtain the desired tensile performance. Figure 4 shows the increment of splitting tensile strength (f_{spf}) as a function of fiber volume fraction (V_f). 17.76 MPa is the highest splitting tensile strength value obtained by the UHPFRC-AG 2.5 mixture, and the maximum improvement observed is 51.4% when compared to its unreinforced counterpart. Plain UHPCC displayed high splitting tensile strength with rapid brittle failure, but UHPFRC with fiber reinforcement exhibited greater splitting tensile strength due to the combined

TABLE 4. Predicted Compressive Strength of UHPFRC

Mix ID	Fiber Volume Fraction (v_f) (%)	28 days Compressive strength (MPa)		Absolute Error (%)
		Experimental values	Predicted values	
UHPCC-AQ	0	132.57	132.57	0.00
UHPFRC-AQ 0.5	0.5	137.61	135.86	1.27
UHPFRC-AQ 1	1	141.32	139.15	1.53
UHPFRC-AQ 1.5	1.5	144.50	142.44	1.42
UHPFRC-AQ 2	2	147.55	145.74	1.23
UHPFRC-AQ 2.5	2.5	149.01	149.03	0.01
UHPCC-AG	0	136.67	136.67	0.00
UHPFRC-AG 0.5	0.5	142.00	140.43	1.10
UHPFRC-AG 1	1	146.24	144.20	1.39
UHPFRC-AG 1.5	1.5	149.93	147.96	1.31
UHPFRC-AG 2	2	153.48	151.73	1.14
UHPFRC-AG 2.5	2.5	155.39	155.49	0.06

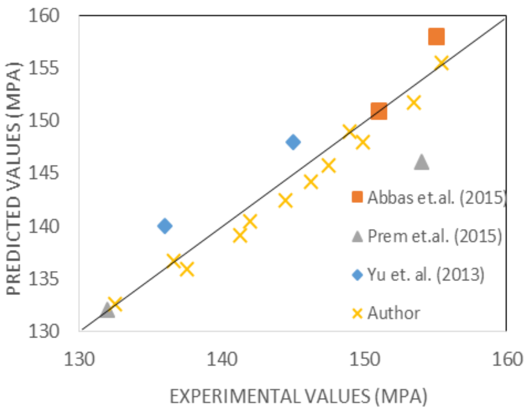


Figure 3. Comparison of experimental values of compressive strength (MPa) of UHPFRC with the predicted values by model

contribution of the UHPFRC matrix and steel fibers to the splitting tensile force. The failure pattern of UHPFRC cylinder specimen under splitting tensile load is shown in Figure 2(b).

The splitting tensile strength values of UHPFRC mixtures can be expressed as a function of fiber volume fraction (V_f) using the linear regression analysis on experimental results presented in Table 3. The splitting tensile strength with respect to steel fiber volume frsaction is shown in Figure 4.

The expressions are stated as follows:

$f_{spf} = f_{sp} + 1.88 (v_f)$ for UHPFRC-AQ (3)

$f_{spf} = f_{sp} + 2.41 (v_f)$ for UHPFRC-AG (4)

The empirical equations developed by using linear regression analysis on experimental values is used to predict the splitting tensile strength values of UHPFRC mixtures and are presented in Table 5.

3. 3. Flexure Strength

The flexural strength values of UHPFRC mixtures with five different steel fiber volume fractions (V_f = 0.5, 1, 1.5, 2, and 2.5%) are presented in Table 3 and subsequently shown in Figure 5. Flexural strength increased with fiber content, reaching a maximum at 2.5% by volume of steel fibers. Out of all the mechanical properties, flexural strength was the most improved parameter with the addition of steel fibers, and a minimum percentage increment of 18.10% for UHPFRC-AQ 0.5. All the test specimens displayed deflection-hardening behavior once steel fibers were added, resulting in greater load-carrying capability after the first crack. The maximum flexural strength obtained was 32.50 MPa for the UHPFRC-AG specimen with 2.5% by volume of steel fibers; this value is 68.9, 49.70, 32.80, 18.30% and 6.20% higher than those of the specimens with 0, 0.5, 1, 1.5 and 2% by volume of steel fibers respectively. These findings suggest that the fiber volume fraction has a significant impact on the post-cracking behavior of UHPFRC, such as strength, deflection, and crack width. The fiber content had a considerable influence on the fracture surface roughness; the roughness increased as the fiber concentration increased. This is because more fibers are randomly dispersed and orientated at the crack surface when the fiber content is higher. The failure pattern of UHPFRC prism specimen under flexural load is shown in Figure 2(d).

The flexural strength values of UHPFRC mixtures can be expressed as a function of fiber volume fraction (Vf) using the linear regression analysis on experimental results presented in Table 3, and the expressions are as follows:

$f_{rf} = f_r + 4.47 (v_f)$ for UHPFRC-AQ (7)

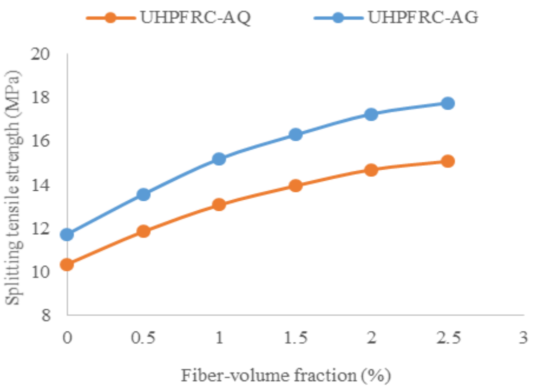


Figure 4. Splitting Tensile strength vs. Steel Fiber Volume Fraction (%)

TABLE 5. Predicted Splitting Tensile Strength of UHPFRC

Mix ID	Fiber Volume Fraction (v_f) (%)	28 days Splitting tensile strength (MPa)		Absolute Error (%)
		Experimental values	Predicted values	
UHPCC-AQ	0	10.35	10.35	0.00
UHPFRC-AQ 0.5	0.5	11.85	11.29	4.69
UHPFRC-AQ 1	1	13.07	12.24	6.37
UHPFRC-AQ 1.5	1.5	13.95	13.18	5.50
UHPFRC-AQ 2	2	14.70	14.13	3.86
UHPFRC-AQ 2.5	2.5	15.08	15.07	0.04
UHPCC-AG	0	11.73	11.73	0.00
UHPFRC-AG 0.5	0.5	13.56	12.94	4.57
UHPFRC-AG 1	1	15.19	14.15	6.85
UHPFRC-AG 1.5	1.5	16.29	15.36	5.73
UHPFRC-AG 2	2	17.25	16.57	3.98
UHPFRC-AG 2.5	2.5	17.76	17.78	0.10

TABLE 6. Predicted Flexural Strength of UHPFRC

Mix ID	Fiber Volume Fraction (v_f) (%)	28 days Flexural tensile strength (MPa)		Absolute Error (%)
		Experimental values	Predicted values	
UHPCC-AQ	0	17.46	17.46	0.00
UHPFRC-AQ 0.5	0.5	20.62	19.70	4.47
UHPFRC-AQ 1	1	23.69	21.94	7.41
UHPFRC-AQ 1.5	1.5	26.09	24.18	7.32
UHPFRC-AQ 2	2	27.64	26.42	4.43
UHPFRC-AQ 2.5	2.5	28.44	28.65	0.75
UHPCC-AG	0	19.24	19.24	0.00
UHPFRC-AG 0.5	0.5	22.93	21.93	4.37
UHPFRC-AG 1	1	26.19	24.62	5.97
UHPFRC-AG 1.5	1.5	28.98	27.31	5.74
UHPFRC-AG 2	2	31.30	30.00	4.15
UHPFRC-AG 2.5	2.5	32.50	32.69	0.61

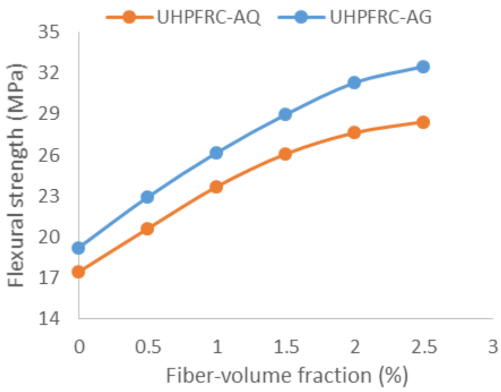


Figure 5. Flexural strength vs. Steel Fiber Volume Fraction (%)

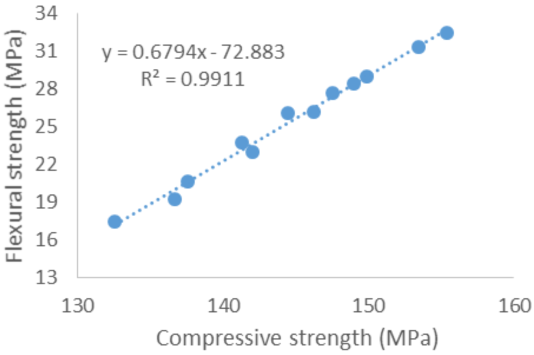


Figure 6. Relation between Flexural Strength and Compressive Strength (MPa) of UHPFRC

$$f_{rf} = f_r + 5.38\,(v_f) \qquad \text{for UHPFRC-AG} \qquad (8)$$

The empirical equations developed by using linear regression analysis on experimental values is used to predict the flexural strength values of UHPFRC mixtures and are presented in Table 6.

3. 4. Relationship between Flexural Strength and Compressive Strength

The relationship between flexural strength and compressive strength of UHPFRC has been obtained using statistical analysis on experimental data and is displayed in Figure 6. The empirical equation for flexural strength of UHPFRC with a correlation coefficient of $R^2 = 0.99$ is as follows:

$$f_{rf} = 0.679 f_{cf} - 72.88 \qquad (10)$$

3. 5. Modulus of Elasticity

The variation of elastic modulus, (E_{cf}) values for the UHPFRC mixtures with the effect of fiber volume fraction (V_f) is presented in Table 7 and Figure 7. Steel fiber addition to UHPCC increased corresponding strain at peak stress, and in turn improved its toughness. The fiber volume fraction has a direct relationship with this behavior. A UHPFRC mixture containing alccofine and quartz powder obtained an elastic modulus value of 39.52 GPa for the unreinforced specimen and 46.32 GPa for the UHPFRC-AQ 2.5, which has a 2.5% steel fiber volume fraction. Similarly, an UHPFRC mixture containing alccofine and GGBS obtained a higher elastic modulus value of 40.74 GPa for an unreinforced specimen and 47.99 GPa for UHPFRC-AG 2.5, having a 2.5% steel fiber-volume fraction. The explosive failure demonstrated by unreinforced UHPCC specimens posed risks and reading measurement

TABLE 7. Modulus of Elasticity of UHPFRC

Mix ID	Fiber Volume Fraction (v_f) (%)	Modulus of elasticity (GPa)
UHPC-AQ	0	39.52
UHPFRC-AQ 0.5	0.5	41.54
UHPFRC-AQ 1	1	43.43
UHPFRC-AQ 1.5	1.5	45.01
UHPFRC-AQ 2	2	45.96
UHPFRC-AQ 2.5	2.5	46.32
UHPC-AG	0	40.74
UHPFRC-AG 0.5	0.5	42.94
UHPFRC-AG 1	1	44.98
UHPFRC-AG 1.5	1.5	46.53
UHPFRC-AG 2	2	47.54
UHPFRC-AG 2.5	2.5	47.99

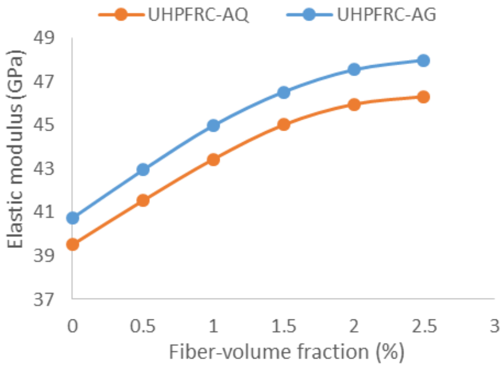


Figure 7. Modulus of elasticity vs. Steel Fiber Volume Fraction (%)

challenges, which are observed in normal concrete but UHPFRC displayed higher compressive strain. According to the crack pattern on tested cylindrical specimens, it was observed that vertical cracks were formed on specimens with lower steel fiber volume fractions and diagonal cracks were formed on specimens with higher steel fiber volume fractions. The failure pattern of UHPFRC cylinder specimen under uni-axial compressive load is shown in Figure 2(c).

The elastic modulus values of UHPFRC mixtures can be expressed as a function of fiber volume fraction (V_f) using the linear regression analysis on experimental results presented in Table 7, and the expressions are as follows:

$$E_{cf} = E_c + 2.79\ (v_f) \quad \text{for UHPFRC-AQ} \quad (11)$$

$$E_{cf} = E_c + 2.94\ (v_f) \quad \text{for UHPFRC-AG} \quad (12)$$

The empirical equation developed by using linear regression analysis on experimental values is used to predict the elastic modulus values of UHPFRC mixtures and are presented in Table 8.

3. 6. Stress-strain Behavior Under stresses developed roughly below the 70% strength of UHPFRC, linear elastic behavior is observed. Figures 8 and 9 show the stress-strain behavior of UHPFRC-AQ and UHPFRC-AG, respectively. From stress-strain curves, it can be observed that a linear ascent is exhibited up to the peak stress. It is also observed that the strain at corresponding peak stresses increases as the fiber volume fraction and strength of UHPFRC mixtures increase. The stress-strain behavior of unreinforced UHPCC specimens showed a sudden dip in stress values and a negligible increment in strain values beyond the peak stress. UHPFRC mixtures displayed a nonlinear strain-hardening phase after the elastic phase, owing to the formation of micro cracks in the concrete matrix. The interlocking of interfacial bonds carried the load instead of the concrete matrix. The higher steel fiber volume fractions of UHPFRC displayed greater interlocking, resulting in higher stress values. Steel fiber volume fraction (V_f) greatly influences the post-peak curve.For the UHPFRC mixtures with lower fiber volume fractions, the post peak curve is nearly as steep as the ascending curve in pre-peak stage, whereas for the UHPFRC mixtures with higher fiber volume fractions, the post peak curve slopes more gradually. There was a minimum influence of V_f on initial stiffness, but in the softening region, higher V_f resulted in greater peak load. A peak stress of 109 MPa was obsereved for UHPCC-AG mixture and a peak stress of 124 MPa was observed for UHPFRC-AG 2.5 mixture.

TABLE 8. Predicted Modulus of Elasticity of UHPFRC

Mix ID	Fiber Volume Fraction (v_f) (%)	Modulus of elasticity (GPa)		Absolute Error (%)
		Experimental values	Predicted values	
UHPCC-AQ	0	39.52	39.52	0.00
UHPFRC-AQ 0.5	0.5	41.54	40.92	1.49
UHPFRC-AQ 1	1	43.43	42.31	2.58
UHPFRC-AQ 1.5	1.5	45.01	43.71	2.90
UHPFRC-AQ 2	2	45.96	45.10	1.87
UHPFRC-AQ 2.5	2.5	46.32	46.50	0.39
UHPCC-AG	0	40.74	40.74	0.00
UHPFRC-AG 0.5	0.5	42.94	42.21	1.69
UHPFRC-AG 1	1	44.98	43.69	2.86
UHPFRC-AG 1.5	1.5	46.53	45.16	2.92
UHPFRC-AG 2	2	47.54	46.64	1.90
UHPFRC-AG 2.5	2.5	47.99	48.11	0.25

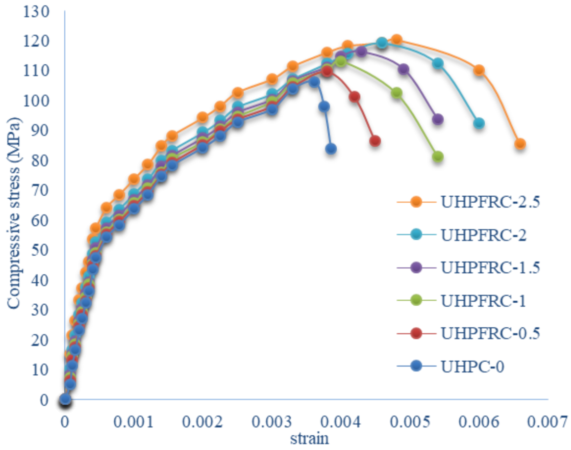


Figure 8. Stress-Strain behavior of UHPFRC-AQ

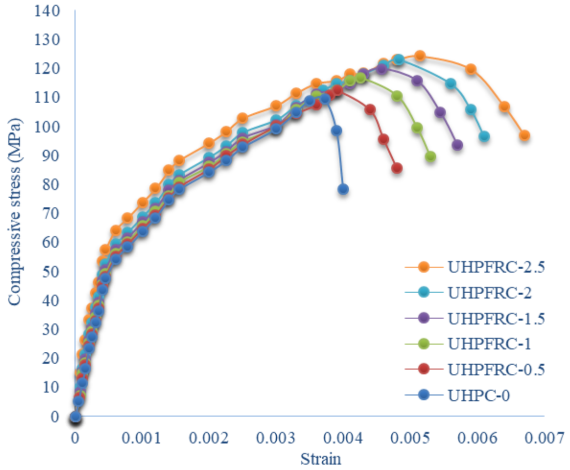


Figure 9. Stress-Strain behavior of UHPFRC-AG

4. CONCLUSIONS

The effect of steel fiber volume fraction on the mechanical performance of UHPCC was investigated, and the following conclusions can be drawn:

- Addition of steel fibers to UHPCC resulted moderate improvement in compressive strength and significant improvement in splitting tensile and flexure strengths. Improvement in strengths observed is 13.7, 51.4, and 68.9% for compressive, splitting tensile, and flexural strengths, respectively for UHPFRC at $V_f = 2.5\%$ compared to UHPCC.
- Addition of steel fibres up to 2% by volume improved the compressive strength and elastic modulus significantly and above 2% of volume fraction, negligible improvement was observed.
- The maximum splitting tensile strength obtained for UHPFRC-AG is 17.76 MPa for UHPFRC with $V_f = 2.5\%$, which is 51.4% higher than the corresponding UHPCC mixture.
- The maximum flexural strength obtained is 32.50 MPa for UHPFRC-AG with $V_f = 2.5\%$, which is 68.9% higher than the corresponding UHPCC mixture.
- For all fiber volume fractions, UHPFRC-AG exhibited superior performance compared to UHPFRC-AQ.
- Empirical equations developed for the prediction of strength properties as a function of steel fiber volume fraction and the predicted values were compared with the experimental data of earlier researchers. It was found that the equations developed, evaluated the strength values with high efficacy.
- Relation between compressive and flexural strengths of UHPFRC has been developed and reliability of the model in predicting the strength is very good.

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Persian Abstract

چکیده

به منظور بررسی اثر کسر حجمی الیاف بر رفتار مکانیکی کامپوزیت های بتن با عملکرد فوق العاده بالا (UHPCC)، پنج کسر حجمی مختلف از الیاف ماکرو فولادی (Vf = 0.5، ۱، ۱.۵، ۲ و ۲.۵٪) در داخل استفاده می شود. ماتریس ملات یکسان مخلوط بتن مسلح با الیاف با کارایی فوق العاده بالا (UHPFRC)برای دستیابی به مقاومت فشاری ۱۵۵ مگاپاسکال بر اساس روش بسته بندی ذرات طراحی شده است. برای ۱۲ سری مخلوط UHPCC، استحکام فشاری، مقاومت کششی شکافی، مقاومت خمشی و مدول الاستیسیته در ۲۸ روز تعیین می‌شود. نتایج آزمایش بهبود قابل توجهی را در استحکام کششی و خمشی UHPFRC با افزودن الیاف فولادی نشان داد. حداکثر مقاومت های فشاری، کششی شکافی و خمشی به ترتیب ۱۵۵.۳۹، ۱۷.۷۶ و ۳۲.۵۰ مگاپاسکال بود. رفتار تنش-کرنش کامپوزیت های بتن تقویت شده با الیاف مورد مطالعه قرار گرفته و مقادیر مدول الاستیک ارزیابی شده در محدوده ۳۹.۵۲-۴۷.۹۹ GPa می باشد. عبارات تجربی بر اساس نتایج آزمایش بر حسب کسر حجمی فیبر برای پیش‌بینی نقاط قوت ۲۸ روزه UHPFRC ایجاد شده‌اند. با مقایسه مقادیر تجربی محققان قبلی با مقادیر پیش‌بینی‌شده توسط معادلات تجربی، میانگین خطای مطلق (AAE)مقدار به‌دست‌آمده در ۵٪ است. پیش‌بینی‌های مدل پیشنهادی مطابقت خوبی با مقادیر تجربی دارد. رابطه بین مقاومت فشاری و خمشی UHPFRC با $R^2=0.99$ توسعه یافته و تایید شده است.