

Strength Modeling of High-Strength Concrete with Hybrid Fibre Reinforcement

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Abstract: The low tensile strength and limited ductility, the unavoidable deficiency, of concrete can be overcome by the addition of fibres. High strength concrete (HSC) of 60 MPa containing hybrid fibres, combination of steel and polyolefin fibres, at different volume fraction of 0.5, 1.0, 1.5 and 2.0% were compared in terms of compressive, splitting tensile strength and flexural properties with HSC containing no fibres. Test results showed that the fibres when used in hybrid form could result in enhanced flexural toughness compared to steel fibre reinforced concrete [HSFRC]. The compressive strength of the fibre-reinforced concrete reached maximum at 1.5% volume fractions and the splitting tensile strength and modulus of rupture improved with increasing volume fraction. Strength models were established to predict the compressive and splitting tensile strength and modulus of rupture of the fibre-reinforced concrete. The models give prediction matching the measurements.

Key words: HSFRC, HYFRC, polyolefin fibre, steel fibre

INTRODUCTION

With the development of high grade cement and availability of proper mineral admixtures and chemical admixtures, it has become quite common to adopt concrete with compressive strength of 60 MPa and above. The resulting structures are slender. Development of high strength concrete has made it possible to build taller and long span structures in concrete that was not otherwise possible^[1,2]. But it has been proved that the comparatively higher compressive strength of HSC is an attractive profit from engineering characteristics and economic point of view whereas, the strength behaves against the ductility of concrete by welcoming brittleness pronouncedly^[3]. To improve the ductility of HSC, a strategy is to introduce steel or polymeric fibres in HSC which results in development of near isotropic material with reasonable tensile strength and greater toughness which prevents the initiation and propagation of cracks^[4-8].

It has also been shown recently^[9-12] that by using the concept of hybridization with two different fibres incorporated in a cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fibre enables the more efficient utilization of the potential properties of the other fibre. However, the hybrid composites studied by previous researchers were focused on hybridization of steel,

polypropylene and carbon fibres. The mechanical properties of hybridization of steel and polyolefin fibres in HSC at different volume fraction (0.5, 1.0, 1.5 and 2.0%) have been studied previously are available limited. Therefore the objective of this research is to determine the basic properties of hybrid fibre reinforced high strength concrete in terms of compressive, splitting tensile and flexural tests in comparison with the plain high-strength counter part and establishes models for predicting the behaviour of HSFRC and HYFRC under compression, splitting tension and flexure.

MATERIALS AND METHODS

The cement used in concrete mixes was ordinary Portland cement 53 grade as per IS 12269-1987. The sand used was local river sand with specific gravity of 2.54. The coarse aggregate was crushed stone with size of 20 mm and 10 mm and specific gravity of 2.67. Silica fume used was a commercially available CONPLAST (MS) in densified form which improved concrete properties in fresh and hardened states. To improve the workability of concrete, a high-range water-reducing admixture [hyper-plasticizer] was used during mixing operations.

The properties of the steel and polyolefin fibres are shown in Table 1 and the concrete mix proportions used in the test program are presented in Table 2.

Preparation of test specimens: In the preparation of concrete, the constituent materials were initially mixed without fibres. The fibres were then added in small amounts to avoid balling of fibres and to produce concrete with uniform material consistency and good workability. The steel fibre reinforced concrete and hybrid fibre reinforced concrete [combination of steel-polyolefin fibres] at different volume fraction of 0.5, 1.0, 1.5 and 2.0% specimens were placed into moulds and a vibrator was used to decrease the amount of air bubbles. The specimens were remolded after 24 h and then placed in a curing tank for 28 days and the

specimens were removed from curing tank and allowed to air dry 12 h prior to test.

Test methods: For each mixture, 150×300 mm cylindrical specimens and 100×100×500 mm beams were prepared. The compressive strength test was carried out on 150x300 mm cylinder specimens as per ASTM C 39. The cylinders were loaded, in a compression testing machine at the rate of 0.3 MPa/s until failure.

The splitting tensile test, on the cylinder specimens, was conducted in accordance with ASTM C 496. In the test, the load was applied continuously at the rate of 0.9 MPa/min. until failure.

The flexural strength (modulus of rupture, MOR) test were conducted on prismatic beam specimens under third-point loading, in accordance with ASTM C 78 for flexural strength of fibreous concrete and ASTM C 1108 for the flexural toughness of fibre reinforced concrete. The beam was loaded gradually to increase the deflection at constant rate.

Table 1 Properties of Fibres used

Fibre details	Fibre properties	
	Polyolefin	Steel
Length (mm)	48	30
Shape	Straight	Hooked at ends
Size/Diameter (mm)	1.22×0.732 mm	0.5 mm
Aspect Ratio	39.34	60
Density (kg m ⁻³)	920	7850
Specific gravity	0.90-0.92	-
Young's modulus (GPa)	6	210
Tensile strength (MPa)	550	532

Table 2: Concrete mix proportions used in the testing program

Material	Quantity
53 Grade cement (Kg m ⁻³)	450
Sand (Kg m ⁻³)	780
Coarse aggregate (Kg m ⁻³)	
20 mm size	680
10 mm size	450
Water (Kg m ⁻³)	160
Silica fume (Kg m ⁻³)	25
Hyper plasticizer (Kg m ⁻³)	25
Slump	100 mm

RESULTS AND DISCUSSION

Table 3 presents the strength test results on HSFRC, HYFRC and HSC. The compressive strength, splitting tensile strength and modulus of HSFRC and HYFRC improved to different extent in response to the fibre volume fraction.

Compressive strength: Figure 1 shows the effect of fibre volume on compressive strength of HSC of 60 MPa. The compressive strength development of HSC and of HSFRC and HYFRC provided an improvement

Table 3: Mechanical properties of fibre-reinforced concretes

Fibre volume (%)			Compressive strength (MPa)		Splitting tensile strength (MPa)		Modulus of rupture (MPa)	
Steel	PO	Total	Measured value	Strength effectiveness (%)	Measured value	Strength effectiveness (%)	Measured value	Strength effectiveness (%)
0.0	0.0	0.0	61.2	0.00	4.86	0.00	7.30	0.00
0.5	0.0	0.5	63.5	3.76	7.67	57.82	9.60	31.51
0.4	0.1	0.5	62.2	1.63	7.90	62.55	9.72	33.15
0.3	0.2	0.5	61.6	0.65	7.39	52.06	9.35	28.08
1.0	0.0	1.0	67.1	9.64	9.90	103.70	11.80	61.64
0.8	0.2	1.0	66.3	8.33	10.00	105.76	12.00	64.38
0.6	0.4	1.0	63.1	3.10	8.90	83.13	11.25	54.11
1.5	0.0	1.5	69.9	14.20	11.26	131.69	12.89	76.58
1.2	0.3	1.5	67.5	10.30	11.45	135.60	13.00	78.08
0.9	0.6	1.5	65.2	6.54	10.80	122.22	12.54	71.78
2.0	0.0	2.0	69.8	14.10	11.70	140.74	13.10	79.45
1.6	0.4	2.0	69.2	13.10	12.50	157.20	13.80	89.04
1.2	0.8	2.0	68.8	12.40	11.64	139.51	13.16	80.27

$$\text{Strength effectiveness} = \frac{\text{HSFRC (or) HYFRC strength-HSC value strength}}{\text{HSC strength}} \times 100 \%$$

at each volume fraction. The compressive strength of HSFRC ranged from 3.76-14.1% at the volume fraction of 0.5-2.0% and no significant improvement at 2.0% volume fraction of steel fibres compared to 1.5% volume fraction. The compressive strength improvement of HYFRC ranged from 0.65-13.1%. The improvements in compressive strength of HYFRC have no significant effect compared to HSC with steel fibres.

Following from the compressive strength test results, the compressive strength f'_c of HSFRC and HYFRC was predicted in terms of fibre volume fraction V_f as

$$f'_c \text{ (MPa)} = A + BV_f + CV_f^2 \quad (1)$$

and applying regression analysis gave

$$f'_c \text{ (MPa)} = 59.946 + 7.97 V_f - 1.336 V_f^2 \quad (2)$$

The compressive strength predictions using Eq. 2 matching with measurements and prediction error is below 2.09% as shown in Table 4.

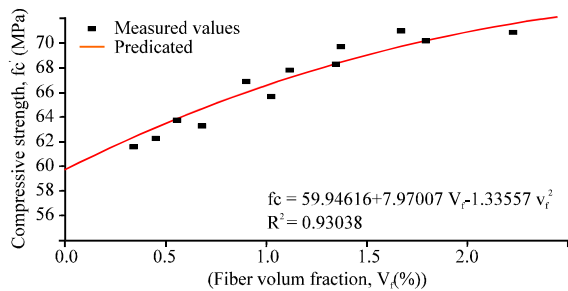


Fig. 1: Effect of fiber volume on compressive strength

At $V_f = 0\%$, Eq. 2 gives the

f'_c value of HSC equal to 59.946 MPa which is f'_c value of concrete used in the study.

Splitting tensile strength: The splitting tensile strength of all the fibrous concrete in this investigation was significantly higher than of plain concrete even at volume fraction as low as 0.5%. The development of splitting tensile strength of HSFRC and HYFRC at various volume fractions is shown in Fig. 2 Compared to HSC, the strength improved with increasing the volume fraction. From the strength effectiveness in Table 3, the improvement started from 57.82-140.74% at the volume fraction of 0.5-2.0% in case of HSFRC and 62.55-157.20% in case of HYFRC.

The splitting tensile strength of HSFRC and HYFRC were predicted using the measured values and the fibre volume fraction of V_f

$$f'_{sp} \text{ (MPa)} = A + BV_f + CV_f^2 \quad (3)$$

and applying regression analysis gave

$$f'_{sp} \text{ (MPa)} = 4.8488 + 8.07901 V_f - 2.28909 V_f^2 \quad (4)$$

At $V_f = 0\%$, Eq. (4) gives the value of f'_{sp} of HSC equal to 4.8488 MPa equal to that given by $0.59 \sqrt{f'_c} = 0.59 \sqrt{60}$, as per ACI 363 R-93 (reapproved 1997). The predicted values matching the measurement and prediction error is below 5.656% as shown in Table 4.

Modulus of rupture: The MOR for HSFRC and HYFRC is shown in Fig. 3. The strength effectiveness in Table 3 indicates that MOR values of all fibrous concrete were significantly higher than of high strength

Table 4: Comparison of predicted and measured values for compressive and splitting tensile strength and modulus of rupture

Fibre volume fraction V_f (%)			Compressive strength			Splitting tensile strength			Modulus of rupture		
Steel	PO	Total	Measured (MPa)	Predicted (MPa)	Prediction error (%)	Measured (MPa)	Predicted (MPa)	Prediction error (%)	Measured (MPa)	Predicted (MPa)	Prediction error (%)
0.0	0.0	0.0	61.20	59.95	-2.09	4.86	4.85	-0.23	7.30	7.04	-3.67
0.5	0.0	0.5	63.50	63.60	0.15	7.67	8.32	7.77	9.60	10.13	5.25
0.4	0.1	0.5	62.20	62.94	1.18	7.90	7.73	-2.17	9.72	9.61	-1.13
0.3	0.2	0.5	61.60	62.26	1.06	7.39	7.10	-4.02	9.35	9.05	-3.29
1.0	0.0	1.0	67.10	66.58	-0.78	9.90	10.64	6.94	11.80	12.20	3.29
0.8	0.2	1.0	66.30	65.52	-1.19	10.00	9.88	-1.17	12.00	11.53	-4.08
0.6	0.4	1.0	63.10	64.32	1.90	8.90	8.93	0.37	11.25	10.68	-5.33
1.5	0.0	1.5	69.90	68.90	-1.46	11.26	11.82	4.71	12.89	13.25	2.74
1.2	0.3	1.5	67.50	67.63	0.19	11.45	11.27	-1.60	13.00	12.76	-1.84
0.9	0.6	1.5	65.20	66.13	1.41	10.80	10.33	-4.52	12.54	11.93	-5.12
2.0	0.0	2.0	69.80	70.54	1.05	11.70	11.85	1.27	13.10	13.29	1.40
1.6	0.4	2.0	69.20	69.32	0.17	12.50	11.92	-4.84	13.80	13.35	-3.38
1.2	0.8	2.0	68.80	67.72	-1.59	11.64	11.32	-2.83	13.16	12.81	-2.74

$$\text{Prediction error} = \frac{\text{Predicted value} - \text{measured value}}{\text{Measured value}} \times 100 \%$$

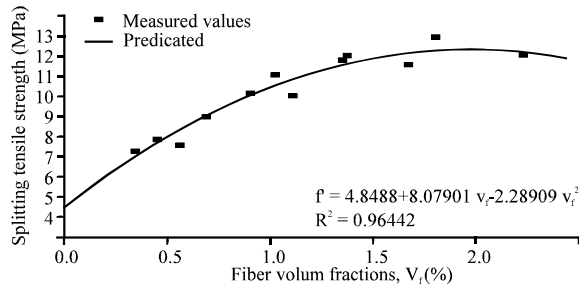


Fig. 2: Effect of fiber volume on splitting tensile strength

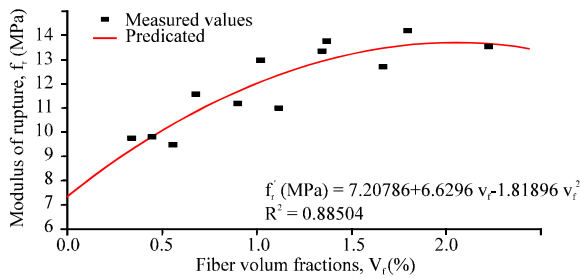


Fig. 3: Effect of fiber volume on modulus of rupture

control concrete even at volume fraction as low as 0.5%. The development of flexural strength of HSFRC and HYFRC at various volume fractions is shown in Fig. 3, compared to HSC. The strength improved with increasing the volume fraction. From the strength effectiveness in Table 3, the improvement started from 31.51-79.45% at the volume fraction of 0.5-2.0% incase of HSFRC 28.08-89.04% incase of HYFRC.

The MOR of HSFRC and HYFRC were predicted using measured values of flexural strength and fibre volume fraction V_f .

$$f'_r \text{ (MPa)} = A + BV_f + CV_f^2 \quad (5)$$

and applying regression analysis gave

$$f'_r \text{ (MPa)} = 7.20786 + 6.6296 V_f - 1.81896 V_f^2 \quad (6)$$

at $V_f = 0\%$ Equ. (6) gives the value of $f'_r = 7.20786$ MPa of HSC equal to that given by $0.94 \sqrt{f'_c} = 0.94 \sqrt{60}$ as per ACI 363R-93 (reapproved 1997). The modulus of rupture predicted matching the measured value and prediction error run below 5.25 % as shown in Table 4.

The comparison of Predicted values by regression analysis and Measured Values for Compressive and Splitting Tensile Strength and Modulus of Rupture of HSFRC and HYFRC are presented in Table 4.

Table 5: Flexural toughness indices

Fibre volume fraction V_f (%)			Toughness index		
Steel	PO	Total	I_5	I_{10}	I_{30}
0.0.	0.0	0.0	3.16	5.89	9.95
0.5	0.0	0.5	4.12	8.25	26.88
0.4	0.1	0.5	4.23	8.74	28.94
0.3	0.2	0.5	4.18	8.79	26.98
1.0	0.0	1.0	4.46	9.18	29.56
0.8	0.2	1.0	4.65	9.35	30.23
0.6	0.4	1.0	4.45	9.25	29.52
1.5	0.0	1.5	5.35	11.75	33.50
1.2	0.3	1.5	5.75	12.65	35.72
0.9	0.6	1.5	5.65	12.35	34.15
2.0	0.0	2.0	7.25	15.23	39.85
1.6	0.4	2.0	7.78	16.25	40.23
1.2	0.8	2.0	7.63	15.72	39.95

Flexural toughness: The toughness of fibre-reinforced concrete can be considered as their energy absorption capacity, which is usually characterized by some portion of the area under the load-deflection curve obtained during flexure test. The flexural toughness indices may be calculated as the ratio of the area under the load- deflection curve for the fibreous concrete to specified endpoints, to the area up to first-crack load, as shown in ASTM C 1018 or to the area obtained for the matrix without fibres.

Three indices defined in ASTM C 1018 are obtained by dividing the area under the load -deflection curve, determined at a deflection that is a multiple of the first-crack deflection, by the area under the curve up to the first-crack. I_5 is determined at a deflection 3 times the first-crack deflection, I_{10} is determined at 5.5 and I_{30} and at 15.5 times the first-crack deflection. These indices increased their values with increasing volume fraction. The I_5 , I_{10} and I_{30} indexes are presented in Table 5. Toughness indices are higher for high-strength hybrid fibreous concrete than for high-strength concrete with steel fibres at each volume fraction.

CONCLUSIONS

There is no significant improvement in compressive strength of HSFRC and HYFRC. Splitting tensile and flexural strength of HSFRC and HYFRC both improved significantly compared to HSC.

The strength effectiveness showed at each volume fraction a maximum for splitting tensile strength, followed by modulus of rupture and compressive strength.

The flexural toughness of HSC improved with addition of fibres at various volume fractions. The flexural toughness of HSC containing fibres in hybrid form observed to have more than the HSFRC.

It is concluded from this investigation that the use of 80% steel fibres and 20% polyolefin fibres at each volume fraction gave optimum mechanical properties. At hybrid fibre of 2.0% volume fraction with 80-20% steel-polyolefin combination have more significant effect on mechanical properties.

Strength models established by regression analysis give predictions matching the measurements of mechanical properties.

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