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Mechanical properties of high strength concrete reinforced with metallic and non-metallic fibres

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Abstract

This paper focuses on the experimental investigation carried out on high strength concrete reinforced with hybrid fibres (combination of hooked steel and a non-metallic fibre) up to a volume fraction of 0.5%. The mechanical properties, namely, compressive strength, split tensile strength, flexural strength and flexural toughness were studied for concrete prepared using different hybrid fibre combinations – steel–polypropylene, steel–polyester and steel–glass. The flexural properties were studied using four point bending tests on beam specimens as per Japanese Concrete Institute (JCI) recommendations. Fibre addition was seen to enhance the pre-peak as well as post-peak region of the load–deflection curve, causing an increase in flexural strength and toughness, respectively. Addition of steel fibres generally contributed towards the energy absorbing mechanism (bridging action) whereas, the non-metallic fibres resulted in delaying the formation of micro-cracks. Compared to other hybrid fibre reinforced concretes, the flexural toughness of steel–polypropylene hybrid fibre concretes was comparable to steel fibre concrete. Increased fibre availability in the hybrid fibre systems (due to the lower densities of non-metallic fibres), in addition to the ability of non-metallic fibres to bridge smaller micro cracks, are suggested as the reasons for the enhancement in mechanical properties.

Keywords: Micro-cracking; Silica fume; Fibre reinforcement; Toughness

1. Introduction

Poor toughness, a serious shortcoming of high strength concrete, can be overcome by reinforcing with short discontinuous fibres. Fibres primarily control the propagation of cracks and limit the crack width [1]. High elastic modulus steel fibres also enhance the flexural toughness and ductility of concrete. The contribution of steel fibres can be observed mainly after matrix cracking in concrete, in that they help in bridging the propagating cracks [2]. The addition of steel fibres at high dosages, however, has potential disadvantages in terms of poor workability and increased cost. In addition, due to the high stiffness of steel fibres, micro-defects such as voids and honeycombs could form during placing as a result of improper consolidation at low workability levels. A compromise to obtain good fresh concrete properties (including workability and reduced early-age cracking) and good toughness of hardened concrete can be obtained by adding two different fibre types, which can function individually at different scales to yield optimum performance [3].

The addition of non-metallic fibres such as glass, polyester, polypropylene etc. results in good fresh concrete properties and reduced early age cracking. The beneficial effects of non-metallic fibres could be attributed to their high aspect ratios and increased fibre availability (because of lower density as compared to steel) at a given volume fraction. Because of their lower stiffness, these fibres are particularly effective in controlling the propagation of micro cracks in the plastic stage of concrete. However, their contribution to post-cracking behaviour, unlike steel fibres, is not known to be significant.

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The hybrid combination of metallic and non-metallic fibres can offer potential advantages in improving concrete properties as well as reducing the overall cost of concrete production [4]. When fibre fractions are increased, it results in a denser and more uniform distribution of fibres throughout the concrete, which reduces shrinkage cracks and improves post-crack strength of concrete. It is important to have a combination of low and high modulus fibres to arrest the micro and macro cracks, respectively. Another beneficial combination of fibres is that of long and short fibres. Once again, different lengths of fibres would control different scales of cracking. A number of studies indicate the overall benefits of using combinations of fibres [5–8].

The objective of this study was to evaluate the mechanical properties of various fibre reinforced concrete systems, containing individual steel fibres and hybrid combinations of steel and non-metallic fibres such as glass, polyester and polypropylene. The total dosage of fibres was maintained at 0.5%, primarily from the point of view of providing good workability. A comparative evaluation of various hybrid fibre concretes was made based on hardened concrete properties – compressive, split and flexural strengths, and flexural toughness.

2. Materials and experimental methods

2.1. Materials used

Ordinary Portland cement conforming to IS 12269 [9] was used for the concrete mixtures. Silica fume, obtained from Elkem Materials, India, was also used for the high strength concrete mixtures. River sand with a specific gravity of 2.65 and fineness modulus of 2.64 was used as the fine aggregate, while crushed granite of specific gravity 2.82 was used as coarse aggregate. A naphthalene sulphonate based superplasticizer was used to obtain the desired workability. The fibres used in the study were hooked steel, polypropylene, polyester, and glass; the properties of these fibres are listed in Table 1.

2.2. Mixture proportioning

Trial mixtures were prepared to obtain target strength of 60 MPa at 28 days, along with a workability of 75–125 mm. In order to obtain the desired workability, only the superplasticizer dosage was varied. The detailed mixture proportions for the study are presented in Table 2, while the volume fractions of various fibres used in the mixtures are given in Table 3.

Table 1
Physical and mechanical properties of the various fibres used

Property	Hooked steel	Polypropylene	Glass	Polyester
Length (mm)	30	20	6	12
Diameter (mm)	0.5	0.10	0.01	0.05
Aspect ratio (l/d)	60	200	600	240
Specific gravity	7.8	0.9	2.72	1.35
Tensile strength (MPa)	1700	450	2280	970
Elastic modulus (GPa)	200	5	80	15
Failure strain (%)	3.5	18	3.6	35

Table 2
Concrete mixture proportions used in the study

Cement (kg/m^3)	Silica fume (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)		Water (kg/m^3)	Superplasticizer dosage[a] (kg/m^3)
			10 mm	20 mm		
372	28	750	570	570	160	8 (Base value)

[a] Varied to obtain desired workability.

Table 3
Dosage of different fibre combinations used in the study

Mixture ID	Volume fraction of hooked steel (%)	Volume fraction of non-metallic fibre (%)	Fibre dosage (kg/m^3)				Total fibre dosage (kg/m^3)
			S	PP	PO	G	
C1	0	–			–	–	–
HST2	0.5	–	38.98	–	–	–	38.98
HSPP3	0.38	0.12	27.22	1.34	–	–	28.56
HSPO4	0.38	0.12	27.22	–	1.82	–	29.04
HSGL5	0.38	0.12	27.22	–	–	3.84	31.06
HSPP6	0.25	0.25	19.44	2.26	–	–	21.70
HSPO7	0.25	0.25	19.44	–	3.36	–	22.80
HSGL8	0.25	0.25	19.44	–	–	6.77	26.21
HSPP9	0.12	0.38	9.36	3.41	–	–	12.77
HSPO10	0.12	0.38	9.36	–	5.14	–	14.50
HSGL11	0.12	0.38	9.36	–	–	10.32	19.68
PP12	–	0.5	–	4.5	–	–	4.50
PO13	–	0.5	–	–	6.72	–	6.72
GL14	–	0.5	–	–	–	13.63	13.63

Note: S: steel fibre; PP: polypropylene fibre; PO: polyester fibre and G: glass fibre.

2.3. Mixing and casting details

The coarse aggregate, fine aggregate, cement, and silica fume were first mixed dry in a pan mixer of capacity 100 kg for a period of 2 min. The superplasticizer was then mixed thoroughly with the mixing water and added to the mixer. Fibres were dispersed by hand in the mixture to achieve a uniform distribution throughout the concrete, which was mixed for a total of 4 min. Fresh concrete was cast in steel moulds and compacted on a vibrating table. The following specimens were prepared:

(i) 100 mm cubes (for compressive strength as per IS 516-1999 [10]);
(ii) 100 mm × 200 mm cylinders (for split tensile strength as per IS 5816-1999 [11]);
(iii) 100 × 100 × 500 mm beam specimens (for flexural tests based on Japanese Concrete Institute (JCI) [12]).

Five specimens each were tested in the case of compressive strength, splitting tensile strength and modulus of elasticity experiments. In the case of flexural tests three beam specimens were used, and the average of these tests is reported in the load–deflection plot, and used for calculating the various parameters. The specimens were demoulded after 24 h, and placed inside a water tank until the age of testing.

2.4. Testing methodology

A universal testing machine of capacity 100 tones was used for testing the compressive strengths of cube specimens at 3, 7, and 28 days from casting at a loading rate of 14 N/mm^2/min, as well as split tensile strengths of cylindrical specimens at 28 days at a loading rate of 1.8 N/mm^2/min. Beams were tested as per JCI specifications, on a displacement controlled testing machine at a rate of 0.05 mm/min. The net deflections at the centre were recorded on to a computer connected through an electronic digital controller system. The load versus displacement curve for each specimen was obtained and the various flexural parameters (flexural strength, residual strength, flexural toughness and equivalent flexural strength) were calculated as per JCI method. A sample load–deflection plot is shown in Fig. 1. It can be seen from this figure that because of the low volume fraction of fibres used, none of the concretes exhibited a true strain hardening behaviour, which is typical of steel fibre reinforced concrete when the fibre content is high.

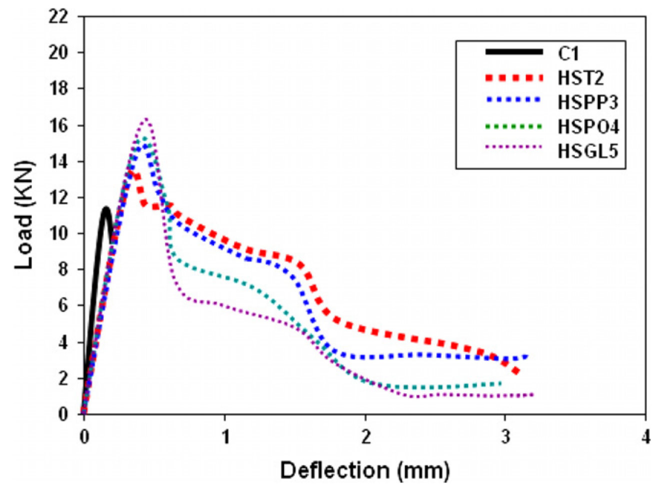

Fig. 1. Typical load–deflection plot for various hybrid fibre concretes.

3. Test results and discussions

3.1. Compressive, split tensile and flexural strength

Results for compressive and split tensile strength and modulus of elasticity for all mixtures are presented in

Table 4
Compressive loading test results of various fibre concretes at 28 days

Serial no.	Mix ID	Compressive strength (MPa)			Split tensile strength (MPa)			Modulus of elasticity (GPa)		
		Mean	SD	COV (%)	Mean	SD	COV (%)	Mean	SD	COV (%)
1	C1	56.1	3.1	5.5	4.1	0.3	4.5	31.1	3.4	11.1
2	HST2	59.2	5.3	8.9	5.2	0.6	6.7	33.2	4.2	12.6
3	HSPP3	61.1	6.3	10.3	5.3	0.3	3.5	34.8	3.7	10.7
4	HSPO4	62.4	3.5	5.7	5.2	0.1	1.1	35.2	3.1	8.8
5	HSGL5	59.2	5.4	9.1	5.3	0.2	8.4	34.1	2.5	7.5
6	HSPP6	64.7	2.3	3.6	5.5	0.1	3.4	35.1	5.2	14.9
7	HSPO7	58.6	4.2	7.2	5.4	0.1	5.5	35.6	3.0	8.4
8	HSGL8	60.3	3.4	5.7	4.9	0.2	3.3	34.5	4.5	13.2
9	HSPP9	63.4	2.2	3.5	4.9	0.3	2.3	35.5	5.2	14.7
10	HSPO10	64.2	6.6	10.3	5	0.1	2.1	35.6	4.2	11.5
11	HSGL11	62	3.1	5.1	4.8	0.7	7.8	34.8	5.7	16.5
12	PP12	56.1	5.8	10.3	4.4	0.5	4.5	33.1	3.1	9.3
13	PO13	55.1	5.1	9.3	4.7	0.2	3.2	34.8	2.8	8.1
14	GL14	57.8	4.1	7.1	4.3	0.4	5.6	33.7	2.2	6.5

Note: SD and COV: standard deviation and coefficient of variation for five specimens.

Table 4. From the results for compressive strength, it is evident that an enhancement in strength compared to control concrete occurs for the steel fibre concrete and all hybrid fibre concretes. However, the concretes with individual non-metallic fibres do not register any increase in strength compared to control concrete. However, the maximum increase in compressive strength is only of the order of 15%. For all fibre concrete mixtures, there was a corresponding increase in the modulus of elasticity compared to the control concrete. It can be seen, however, that the difference in performance of the steel fibre concrete and the hybrid fibres concretes with respect to compressive strength and modulus of elasticity is not significant.

Split tensile strengths of hybrid fibre concretes were found to be higher compared to reference and mono-steel fibre concrete. From Table 4, it can be observed that the hybrid fibre concretes containing steel and Polypropylene (HSPP3 and HSPP6) show the best split tensile strength among all concretes. Enhancement in split tensile strength is expected with fibres since the plane of failure is well defined (diametric). The higher the number of fibres bridging the diametral 'splitting' crack, the higher would be the split tensile strength. However, fibre availability is not the only parameter governing the strength; the stiffness of the fibre is also a major parameter affecting the strength. The increased fibre availability of polyester and polypropylene fibres, combined with the high stiffness of steel fibres, resulted in a significant enhancement of the split tensile strength for these combinations. Glass fibres, possibly owing to their short lengths, did not perform as well as the other two non-metallic fibres.

Flexural testing results are presented in Table 5. Compared to control concrete without fibres, all fibre-reinforced concretes showed an appreciable increase in flexural strength (trend shown in Fig. 2). Among all fibre concretes, the hybrid combination of steel and polyester showed the maximum flexural strength. The reason could be due to smaller length and high aspect ratio of polyester fibres,

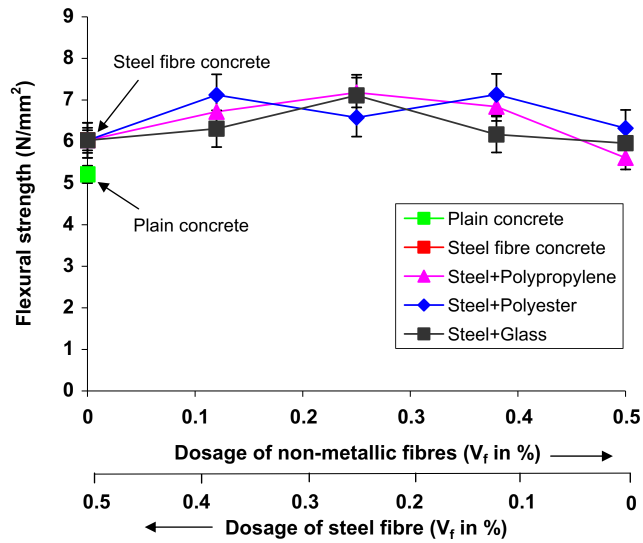

Fig. 2. Flexural strength of various hybrid fibre concretes.

which gives high reinforcement index. In addition, the increased fibre availability makes it more efficient in delaying the growth of micro cracks and thereby improving the ultimate tensile stress capacity. Similarly the steel–polypropylene and steel glass combination showed a reasonable increase in flexural strength compared to the plain and mono-steel fibre concretes. These trends can be explained using the same concepts of increased fibre availability and higher reinforcement index property, as observed in the case of splitting tensile strength.

Also listed in Table 5 are the residual loads for the concretes in flexure, which indicate the load carrying capacity of the material even after failure. These were determined experimentally by loading the specimen up to the peak load, unloading, and then reloading to failure. The steel polypropylene hybrid combination showed the maximum residual load among all hybrid fibre concretes, while the

Table 5
Flexural loading test results for various fibre concretes at 28 days

Mixture ID	Hooked steel V_f (%)	Non- metallic fibre V_f (%)	Ultimate load (kN)	Residual load (kN)	Ultimate flexural strength (MPa)	Flexural toughness (up to 3 mm deflection) (N-m)	Equivalent flexural strength (MPa)
C1	0	–	11.6	0	5.21	1.74	0
HST2	0.5	0	13.4	9.1	6.03	21.36	3.2
HSPP3	0.38	0.12	14.9	9.3	6.72	22.67	3.4
HSPO4	0.38	0.12	15.8	9.1	7.12	19.45	2.92
HSGL5	0.38	0.12	14.1	2.5	6.31	15.23	2.28
HSPP6	0.25	0.25	15.9	5.4	7.18	18.11	2.56
HSPO7	0.25	0.25	14.6	4.8	6.58	17.02	2.25
HSGL8	0.25	0.25	15.8	1.3	7.11	13.56	2.03
HSPP9	0.12	0.38	15.2	4.1	6.84	15.19	1.53
HSPO10	0.12	0.38	15.8	0	7.13	10.17	1.08
HSGL11	0.12	0.38	13.7	0	6.17	10.45	0.67
PP12	–	0.5	12.5	2.2	5.61	7.92	0.63
PO13	–	0.5	14.1	0	6.32	5.98	0.52
GL14	–	0.5	13.2	0	5.96	6.25	0.33

concretes with glass fibres fared the worst. The retention of load carrying capacity after failure decreased with an increase of the non-metallic fibre content in the hybrid combinations, indicating that the main contributor to the residual load was the steel fibres.

3.2. Toughness and equivalent flexural strength

The toughness of fibre reinforced concrete is a measure of the energy absorption capacity of the fibres and is characterized by the area under the load–deflection curve up to a specific deflection. The real effects of fibre addition can be observed as a result of the bridging stress offered by the fibres after the peak load. The equivalent flexural strength for four point bending proposed by JCI [12] is given by

$$\sigma_b = [T_b L]/[\delta_{tb} b h^2]$$

where σ_b is the equivalent flexural strength (N/mm^2); T_b is flexural toughness (N-mm); δ_{tb} is deflection of 1/150 of span (mm); b, d, L is width, depth, and length of section (mm).

The toughness and equivalent flexural strength values calculated as per JCI specifications for various fibre concretes are given in Table 5, and are plotted in Figs. 3 and 4.

The trends observed in Fig. 3 indicate that all the fibre concretes yield a higher flexural toughness compared to plain concrete without fibres. Compared to mono-steel fibre concrete, only the steel–polypropylene combination, for a low dosage of polypropylene fibres (0.12%) was tougher, indicating a possible synergy in the action of these two fibres. However, all other fibre combinations performed worse than the individual steel fibre concrete, and the toughness was found to decrease with an increase in the dosage of the non-metallic fibre. The result seems to indicate that the post-peak behaviour, which contributes mainly to the difference in toughness between the concrete without fibres and concrete with fibres, is mainly dominated by the steel fibres. In the case of the steel–polypropylene fibre concrete (with polypropylene fibres at 0.12%), there was an enhancement over the individual steel fibre concrete possibly as a result of the contribution by polypropylene fibres at small crack widths. Compared to the polyester and glass fibres that were single strand fibres, the polypropylene fibres were fibrillated, which could have resulted in an improved post-peak performance. However, with increasing dosages of polypropylene fibres, there is a decrease in toughness of the steel–polypropylene concrete, since there are not enough steel fibres in the system for bridging the wider cracks. The worst performance was seen with the steel–glass fibre combination, possibly due to the short length of the glass fibres (fibres get pulled out easily). The results in Table 5 and Fig. 4 indicate that the equivalent flexural strength follows the same trend as the toughness.

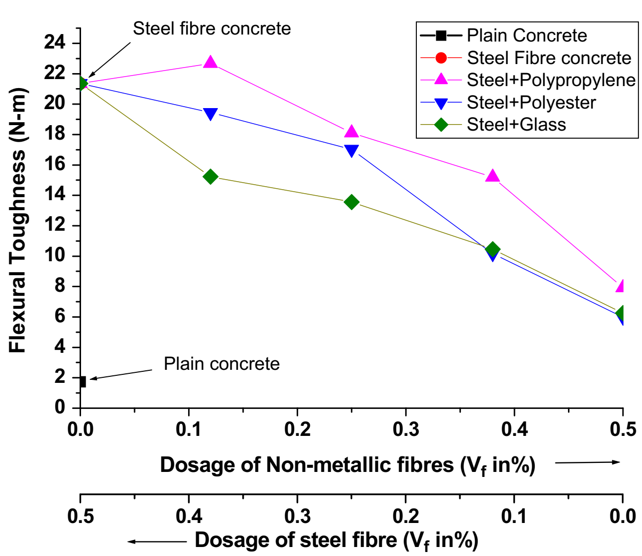

Fig. 3. Flexural toughness of various hybrid fibre concretes.

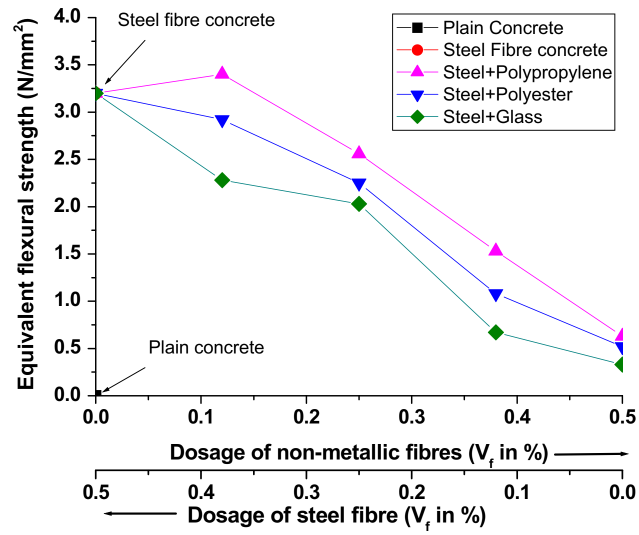

Fig. 4. Equivalent flexural strength of various hybrid fibre concretes.

From the results, it is evident that the ductility of fibre reinforced concrete depends primarily on the fibre's ability to bridge the cracks at high levels of strain. Thus, stiffer fibres would provide better crack bridging; this explains the good performance of steel fibres compared to polyester or polypropylene. Although, the glass fibres have a reasonably high stiffness and tensile strength, they get pulled out easily at high crack widths because of their smaller lengths, and thus do not contribute significantly to the post-peak performance compared to steel fibres.

4. Conclusions

The primary objective of this study was to evaluate the action of hybrid fibres at different volume fractions to obtain a good post-peak behavior of high strength concrete. Results from the study indicate the following:

- It is possible to produce fibre concrete composites using polypropylene, glass and polyester fibres in combination with steel fibres, with an enhanced pre-peak and post-peak performance compared to concrete without fibres.
- Among all hybrid fibre combinations, only the steel polypropylene combination (with 0.12% polypropylene fibres) performed better in all respects compared to the mono-steel fibre concrete. All the other combinations, although giving similar or better strengths, resulted in decreased flexural toughness. The decrease in toughness was more when the proportion of non-metallic fibre was increased.
- Glass fibres performed the worst with respect to toughness (primarily, post-peak) owing to their propensity for getting pulled out because of their short lengths.
- Increased fibre availability in hybrid fibre systems (due to the lower densities of non-metallic fibres), in addition to the ability of non-metallic fibres in bridging smaller micro-cracks, could be the reasons for the enhancement in strength and flexural properties. On the other hand, the inability of non-metallic fibres to sustain high crack widths resulting at large deflections causes the post-peak performance to be poorer compared to individual steel fibre concrete.

A major significance of these findings is that steel fibres in concrete could be replaced to a small extent with non-metallic fibres (mainly polypropylene) to provide a similar toughness to steel fibre concrete. In addition, early age crack resistance can be offered by polymeric fibres (polypropylene and polyester – this aspect is being studied separately by the authors). Thus, hybrid fibre composites combining steel and polypropylene fibres have the potential for large scale use in concrete construction.

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