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Full Length Research Paper

Influence of hybrid fibres on the post crack performance of high strength concrete: Part I experimental investigations

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This paper discusses the experimental results of tests carried out on the flexural properties of various fibre-reinforced concretes at low volume fractions of fibres upto 0.5%. The flexural properties, namely flexural strength, toughness, and ductility, were measured using four point bending tests on beam specimens. Compared to reference concrete without fibres, fibre addition was seen to enhance the pre-peak as well as post-peak region of the load-deflection curve significantly. The best flexural performance was obtained at the highest volume fraction of 0.5%. At this volume fraction, flexural toughness and ductility of hybrid fibre concretes (incorporating a blend of steel and non-metallic fibres) were comparable to steel fibre concretes. 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 of bridging smaller micro cracks, are suggested as the reasons for the enhancement in flexural properties.

Key words: Micro cracking, silica fume, fibre reinforcement, toughness.

INTRODUCTION

Poor toughness, a serious shortcoming of high strength concrete, could be overcome by reinforcing with short discontinuous fibres. Fibres primarily control the propagation of cracks and limit the crack widths (Qian and Stroeven, 2000). 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, when they help in bridging the propagating cracks (Stroeven and Babut, 1986). 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 ductility of hardened concrete can be achieved by adding two different fibre types, which can function individually at different scales to yield optimum performance (Yao et al., 2003).

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 microcracks in the plastic stage of concrete. However, their contribution to post-cracking behaviour, unlike steel fibres, is not known to be significant.

Use of hybrid combinations of steel and non-metallic fibres can offer potential advantages in improving concrete properties as well as reducing the overall cost of concrete production (Bentur and Mindess, 1990). 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 (Pierre et al., 1999; Soroushianp et al., 1992; Bayasi and Zeng,

Table 1. Concrete mixture proportions used in the study.

Mix Id	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 (kg/m^3)
				10 mm	20 mm		
Controlled concrete (C1)	372	28	750	570	570	160	8
All Fibre concrete mixtures	372	28	750	570	570	160	8

Table 2. Properties of the different fibres used.

Property	Hooked steel	Polypropylene	Glass	Polyester
Length (mm)	30	20	12	12
Diameter (mm)	0.5	0.12	0.01	0.03
Aspect ratio (l/d)	60	166	1200	400
Density (kg/m^3)	7800	900	2720	1350
Tensile strength (GPa)	1.7	0.45	2.5	0.92
Elastic modulus (GPa)	200	5	80	15
Failure strain (%)	3.5	18	3.6	12

1993; Banthia and Nandakumar, 2003).

The objective of this study was to evaluate the flexural properties, namely, flexural strength, toughness, and ductility, of different fibre reinforced concrete systems, containing individual steel fibres and hybrid combinations of steel and non-metallic fibres such as glass, polyester and polypropylene. The fibres were added at low dosages, primarily from the point of view of providing good workability, and the overall volume fraction varied between 0.3 and 0.5%. A factorial experimental design was carried out and the flexural properties of various concretes were evaluated.

MATERIALS AND METHODS

Materials used

Ordinary Portland Cement conforming to IS 12269 (Indian Standard Designation, IS 12269-1987) 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, from local manufacturers.

Mixture proportioning

Trial mixtures were prepared to obtain target strength of 60 MPa at 28 days, along with a workability of 75 to 120 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 1, while the properties and volume fractions of various fibres used in the mixtures are given in Tables 2 and 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 (Indian Standard Designation, IS 516-1999)
ii) 100 x 200 mm cylinders (for split tensile strength as per IS 5816 - 1999 (Indian Standard Designation, IS5816-1999)
iii) 100 x 100 x 500 mm beam specimens for flexural tests based on ASTM C1018 (ASTM Standard Designation C 1018-97).

Testing methodology

A universal testing machine of capacity 100 tonnes was used for testing the compressive strengths of cube specimens at 3, 7 and 28 days from casting at a loading rate of 140 $kg/cm^2/min$, 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 ASTM C-1018, on a servo-controlled universal testing machine at a displacement-controlled rate of 0.05 mm/min. The support and mid span deflections were recorded on to a computer connected through an electronic digital controller system. A snapshot of the experimental setup is shown in Figure 1. The load versus displacement curve for each specimen was obtained and the toughness parameters, namely, absolute toughness, toughness indices (I_5, I_{10}, and I_{20}), and residual strength factors ($R_{5,\ 10}$ and $R_{10,\ 20}$) were calculated based on ASTM C1018. The load-deflection plots obtained for different fibre volume fractions are given in Figures 2, 3 and 4. The toughness indices and residual strength factors are calculated using the following equations:

I_5 = Area up to 3.0 times the first crack deflection / area up to first crack (1)

Table 3. Volume fractions of different fibre combinations used in the study.

Mixture ID	Hooked steel (%)	Percentage replacement of steel fibre by non-metallic fibre	Polypropylene (%)	Glass (%)	Polyester (%)	Total fibre dosage (V_f in %)	Steel to non-metallic fibre ratio
C1	0	0	0	0	0	0	-
HSPP1	0.21	30	0.09	-	-	0.3	2.33
HSG2	0.24	20	-	0.06	-	0.3	4
HSPO3	0.27	10	-	-	0.03	0.3	9
HSPP4	0.32	20	0.08	-	-	0.4	4
HSG5	0.36	10	-	0.04	-	0.4	9
HSPO6	0.28	30	-	-	0.12	0.4	2.33
HSPP7	0.45	10	0.05	-	-	0.5	9
HSG8	0.35	30	-	0.15		0.5	2.33
HSPO9	0.40	20	-	-	0.1	0.5	4
HSPP10	0.24	20	0.06		-	0.3	4
HSG11	0.27	10	-	0.03	-	0.3	9
HSPO12	0.21	30	-	-	0.09	0.3	2.33
HSPP13	0.36	10	0.04		-	0.4	9
HSG14	0.28	30	-	0.12	-	0.4	2.33
HSPO15	0.32	20	-	-	0.08	0.4	4
HSPP16	0.35	30	0.15	-	-	0.5	2.33
HSG17	0.40	20	-	0.1		0.5	4
HSPO18	0.45	10	-	-	0.05	0.5	9
HSPP19	0.27	10	0.03	-	-	0.3	9
HSG20	0.21	30	-	0.09	-	0.3	2.33
HSPO21	0.24	20	-	-	0.06	0.3	4
HSPP22	0.28	30	0.12	-		0.4	2.33
HSG23	0.32	20		0.08	-	0.4	4
HSPO24	0.36	10	-	-	0.04	0.4	9
HSPP25	0.40	20	0.1	-	-	0.5	4
HSG26	0.45	10	-	0.05	-	0.5	9
HSPO27	0.35	30	-	-	0.15	0.5	2.33
HST1	0.5	0	-	-	-	0.5	-
HST2	0.4	0	-	-	-	0.4	-
HST3	0.3	0	-	-	-	0.3	-

I_{10} = Area up to 5.5 times the first crack deflection / area up to first crack (2)

I_{20} = Area up to 10.5 times the first crack deflection / area up to first crack (3)

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

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

Experimental design

A factorial experimental design was adopted in this study. The governing factors chosen in this study were (1) total fibre dosage (TFD), (2) steel to non-metallic fibre ratio (SNMFR), and (3) type of fibre combinations (that is steel-glass, steel-polypropylene etc.). These factors were set at three levels each. The various factors and their levels are given in Table 4. The full factorial experimental design consisted of 3^3 (= 27) experimental points with two replicates. In addition to the 27 main experiments, an additional four concrete mixtures were cast for reference, which included one controlled concrete without fibres and three steel fibre concretes at three dosage levels (0.3, 0.4, and 0.5%). The flexural parameters measured were toughness, ductility and flexural strength, and nine experimental design points were evaluated at each level.

TEST RESULTS AND DISCUSSION

Compressive, split tensile and flexural strength

Results for compressive, split tensile and flexural strength for all mixtures are presented in Table 5. It can be seen that for all the fibre concrete mixtures, the compressive

Figure 1. Experimental setup of flexural test.

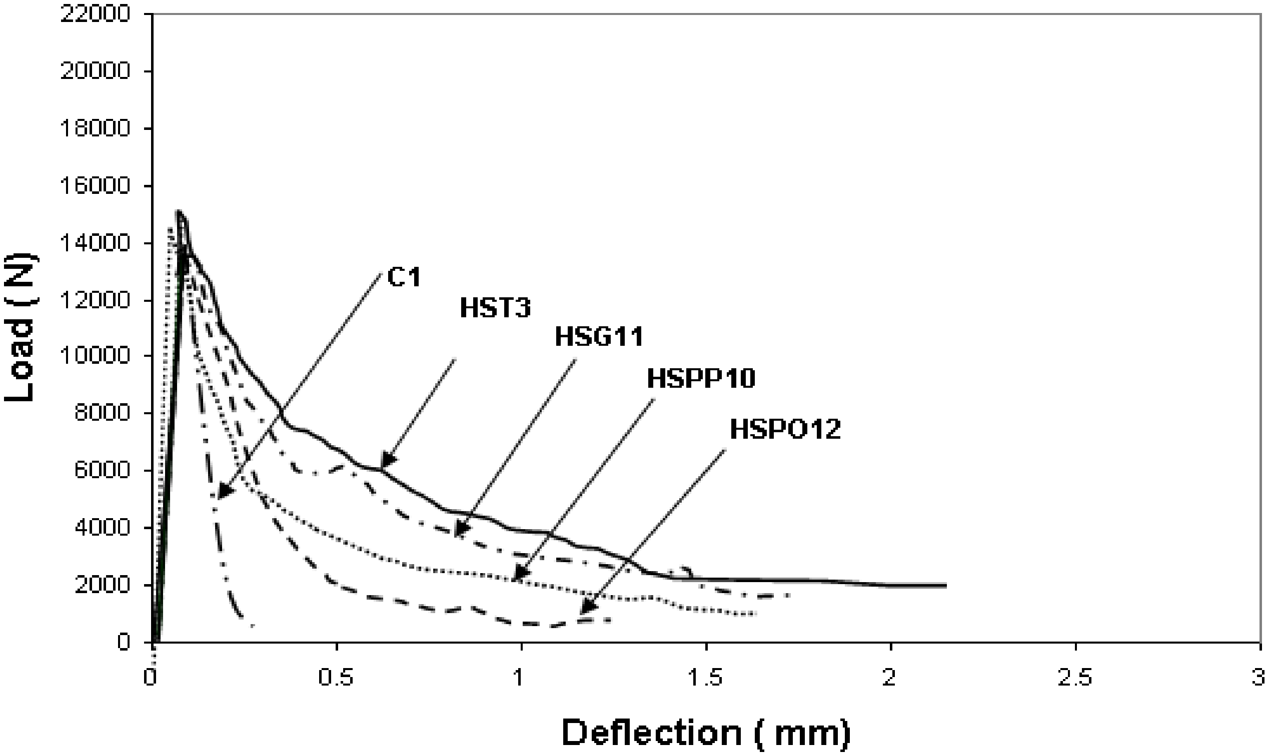

Figure 2. Plot of load versus deflection for various hybrid fibre reinforced concretes at total fibre volume fraction of 0.3 %.

strength at 28 days lies in the range of 58 to 66 MPa, and does not show an appreciable increase compared to controlled concrete. Generally, fibre addition does not affect the compressive strength of concrete significantly, since the mode of crack opening could be other than fracture, in which case the crack bridging effect of the

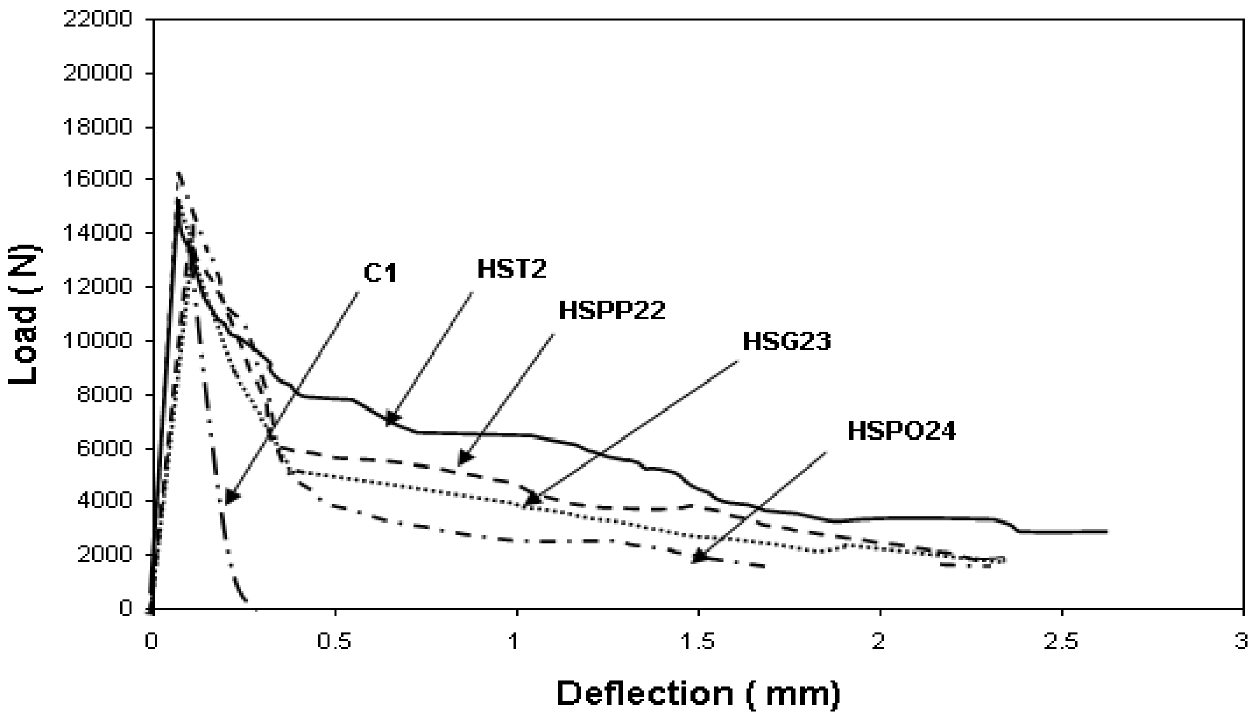

Figure 3. Plot of load versus deflection for various hybrid fibre reinforced concretes at total fibre volume fraction of 0.4%.

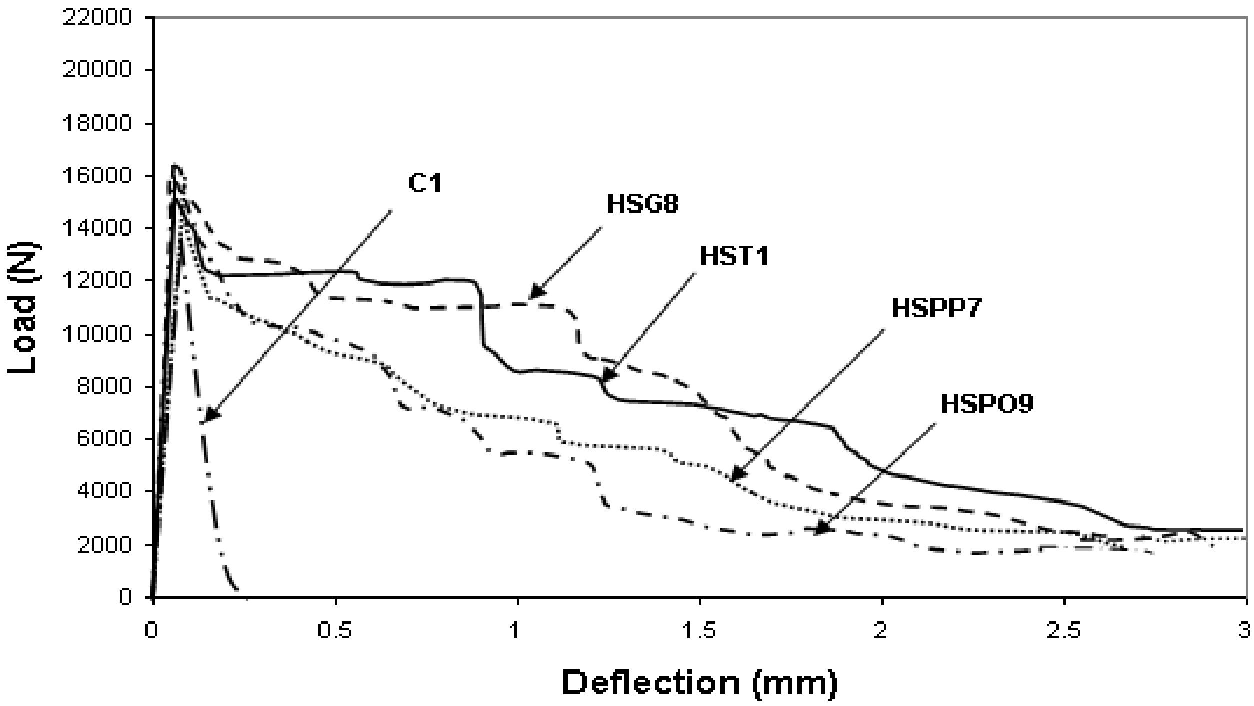

Figure 4. Plot of load versus deflection for various hybrid fibre reinforced concretes at total fibre volume fraction of 0.5%.

fibres is not efficient.

The split tensile strength of hybrid fibre concrete was found to be higher compared to reference and mono steel fibre concrete. From Table 5, it can be observed that the hybrid fibre concretes containing steel and glass at all volume fractions show the best split tensile strength among all concretes at all dosages. Among other combinations, only the steel-polypropylene combination

Table 4. Details of factorial experimental design.

Factors	Level 1	Level 2	Level 3
Total Fibre dosage TFD (% by volume of concrete)	0.3	0.4	0.5
Steel to Non-metallic fibre ratio SNMFR	2.33	4	9
Hybrid Fibre Combinations	Steel + polyester	Steel + glass	Steel + polypropylene
No. of experiments	9	9	9

Table 5. Strength resultsof various concrete mixtures at 28 days.

Mix ID	Fibre volume fraction (%)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)
C1	0	62.9	5.87	5.72
HSPP1	0.3	63.4	6.10	6.40
HSG2	0.3	64.2	6.31	6.19
HSPO3	0.3	62.0	5.89	6.05
HSPP4	0.4	66.7	6.46	6.52
HSG5	0.4	58.7	6.28	6.40
HSPO6	0.4	60.4	5.91	6.42
HSPP7	0.5	61.2	7.30	6.58
HSG8	0.5	64.4	7.67	7.75
HSPO9	0.5	59.3	6.68	6.74
HSPP10	0.3	62.0	6.19	6.35
HSG11	0.3	65.4	6.60	6.11
HSPO12	0.3	61.4	6.21	6.18
HSPP13	0.4	66.7	6.89	6.46
HSG14	0.4	64.2	6.33	6.71
HSPO15	0.4	60.2	6.17	6.31
HSPP16	0.5	64.6	7.71	7.78
HSG17	0.5	64.4	7.56	7.52
HSPO18	0.5	59.3	6.76	6.68
HSPP19	0.3	62.1	6.18	6.12
HSG20	0.3	65.7	6.69	6.32
HSPO21	0.3	62.9	6.15	6.11
HSPP22	0.4	64.4	6.51	6.55
HSG23	0.4	60.2	6.55	6.48
HSPO24	0.4	59.2	6.24	6.29
HSPP25	0.5	61.2	7.45	7.53
HSG26	0.5	64.4	7.91	7.40
HSPO27	0.5	59.3	6.81	6.92
HST1	0.5	60.3	7.46	7.14
HST2	0.4	63.6	6.68	6.50
HST3	0.3	65.3	6.11	6.40

at a dosage of 0.5% (with 30% polypropylene fibres) gave strength higher than the mono-steel fibre concrete. 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 diametric ‘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. Thus, although in terms of availability, the glass and polypropylene fibres in hybrid combinations with steel result in higher fibre availability, only the glass fibres are able to enhance the strength at all dosages owing to their high stiffness. Polyester fibres, however, resulted in lowering of strengths; this might be because of difficulty in dispersing these fibres uniformly into the concrete mixture.

Table 6. Ductility, toughness indices and residual strength of concrete mixtures at a total fibre volume fraction of 0.5%.

Mix ID	Fibre combination	First crack deflection δ (mm)	Ductility $D=\delta_R - \delta$ (mm)	Toughness Indices			Absolute toughness (N m)	Residual strength factors		Post-crack strength (MPa)
				I_5	I_{10}	I_{20}		$(R_{5,10})$	$(R_{10,20})$	
C1	-	0.21	0	-	-	-	4.45	-	-	-
HSPP7	S – PP(90 – 10)	0.24	2.62	4.05	7.23	18.65	19.28	63.6	114.2	4.10
HSPP25	S – PP(80 – 20)	0.21	2.69	4.26	7.42	18.32	20.61	63.2	109.0	4.25
HSPP16	S – PP(70 – 30)	0.24	2.75	4.48	7.75	18.06	21.20	65.4	103.1	4.47
HSG26	S – G(90 – 10)	0.20	2.74	4.67	7.61	18.82	19.63	58.8	112.1	4.16
HSG17	S – G(80 – 20)	0.25	2.78	4.88	7.86	18.57	20.78	59.6	107.1	4.33
HSG8	S – G(70 – 30)	0.24	2.87	5.04	8.35	18.44	21.92	66.2	100.9	4.67
HSPO18	S – PO(90 – 10)	0.21	2.52	4.20	6.70	14.78	18.20	50.0	80.8	3.56
HSPO9	S – PO(80 – 20)	0.23	2.44	3.53	5.35	12.92	17.69	36.4	75.7	3.11
HSPO27	S – PO(70 – 30)	0.24	2.29	3.19	4.78	11.68	17.02	31.8	69.0	2.82
HST1	S(100)	0.26	2.92	4.80	7.78	19.28	21.36	59.6	115.0	4.55

Note: S – Steel fibre, PP – Polypropylene fibre, PO – Polyester fibre, and G – Glass fibre.

Compared to the control concrete without fibres, all fibre-reinforced concretes showed higher flexural strengths. Among all fibre concretes, the hybrid combination of steel and glass was once again the best. In certain combinations, the steel-polypropylene combination also performed better than the mono-steel mixtures. Additionally, the steel-polyester combination resulted in lower strengths than other fibre concretes. These trends can be explained using the same concepts of fibre availability and stiffness, as in the case of the splitting tensile strength.

Toughness indices and absolute toughness

The absolute toughness of fibre reinforced concrete is a measure of the strain energy stored in the material. It is characterized by the area under the entire load-deflection plot and realized appropriately in terms of toughness indices. The various toughness indices (I_5, I_{10}, and I_{20}), calculated as per ASTM C-1018 and absolute toughness values of hybrid fibre concrete mixtures and mono fibre concrete mixtures at a volume fraction of 0.5% are given in Table 6.

The trends observed in Figure 5 indicate that all the fibre concretes yield a higher absolute toughness compared to the controlled concrete without fibres. Compared to the mono-steel fibre concrete, both the steel-glass combination and the steel-polypropylene combination gave similar toughness values. On the other hand, the toughness of steel-polyester concretes is lower compared to the mono-steel fibre concrete. In the case of the toughness indices (I_5 and I_{10}) also, the same trends are observed (Figures 6 and 7), in that the steel-glass and steel-polypropylene combinations give a comparable performance to the mono-steel fibre concrete, while the toughness indices for the steel-polyester combination are lower at higher fractions of polyester fibres. Once again, the poor performance of the steel-polyester combination could be attributed to the insufficient dispersion of polyester fibres.

Another notable trend that emerges from the results is that, for the steel-glass and steel-polypropylene combination, the higher the replacement of steel with the non-metallic fibre, the higher the toughness (and the indices). However, this trend is just the opposite for the steel-polyester combinations. It is difficult to explain this trend with the available data. However, it can be safely concluded that some of the steel fibres could be effectively replaced using non-metallic fibres without compromising on the toughness. The contribution to the I_5 is at a low deflection level, and the cracks at this stage, being small in width, are effectively bridged by the non-metallic fibres like glass and polypropylene. On the other hand, in the calculation of I_{20}, a high level of deflection is used, and the wide cracks at

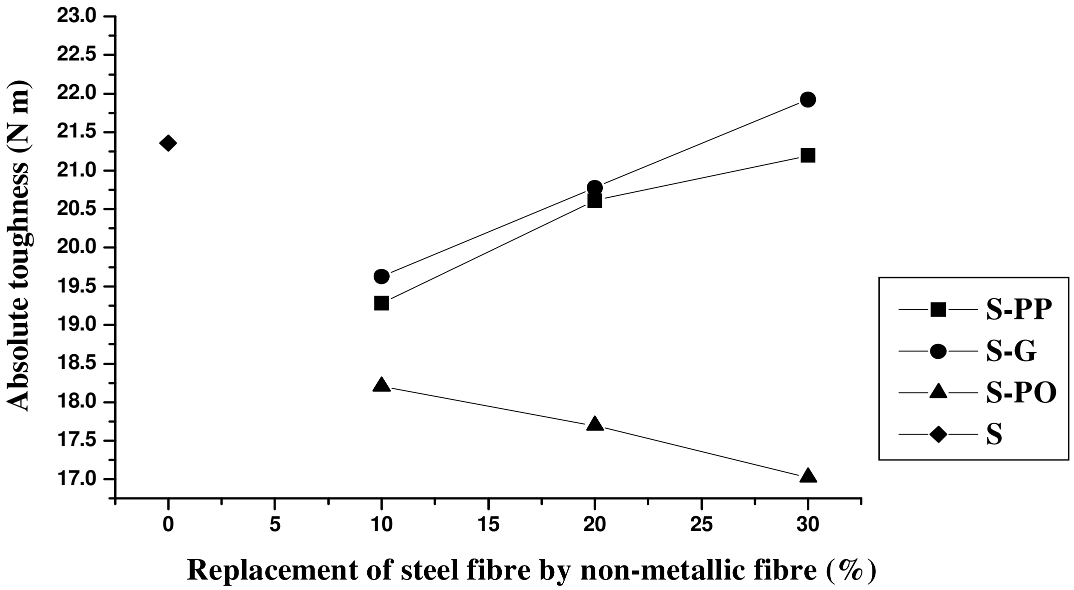

Figure 5. Plot of absolute toughness versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

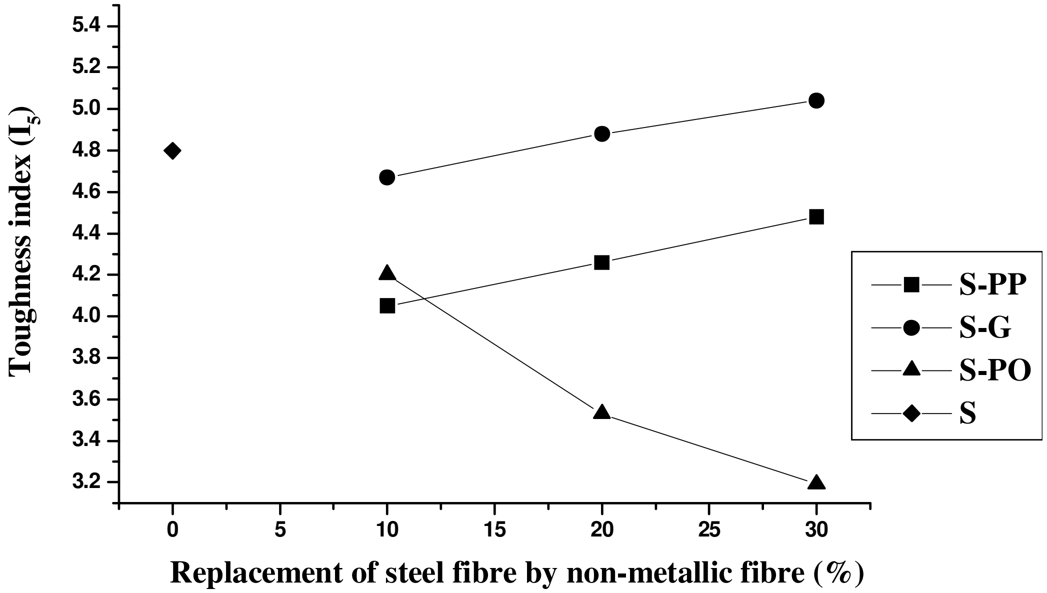

Figure 6. Plot of toughness index (I_5) versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

this stage possibly need the action of steel fibres; this can be seen from Figure 8.

Residual strength factors (RSF)

RSFis obtained directly from toughness indices and represent the level of strength retained after first crack (ASTM Standard Designation C 1018-97). The residual strength factors calculated based on ASTM C-1018 for the various concretes are given in Table 6. The observed trends for the residual strength factors are shown in Figures 9 and 10. It is observed from Figure 9 that the RSF ($R_{5,10}$) for steel–glass and steel-polypropylene fibre concretes were higher than mono-steel fibre concrete at higher fractions of glass and polypropylene fibres, which dominated the post peak region of the load –deflection plot up to 5.5δ (where δ is the first crack deflection). However, it can be seen from Figure 10 that the RSF ($R_{10,\ 20}$) of mono steel fibre concrete was higher than

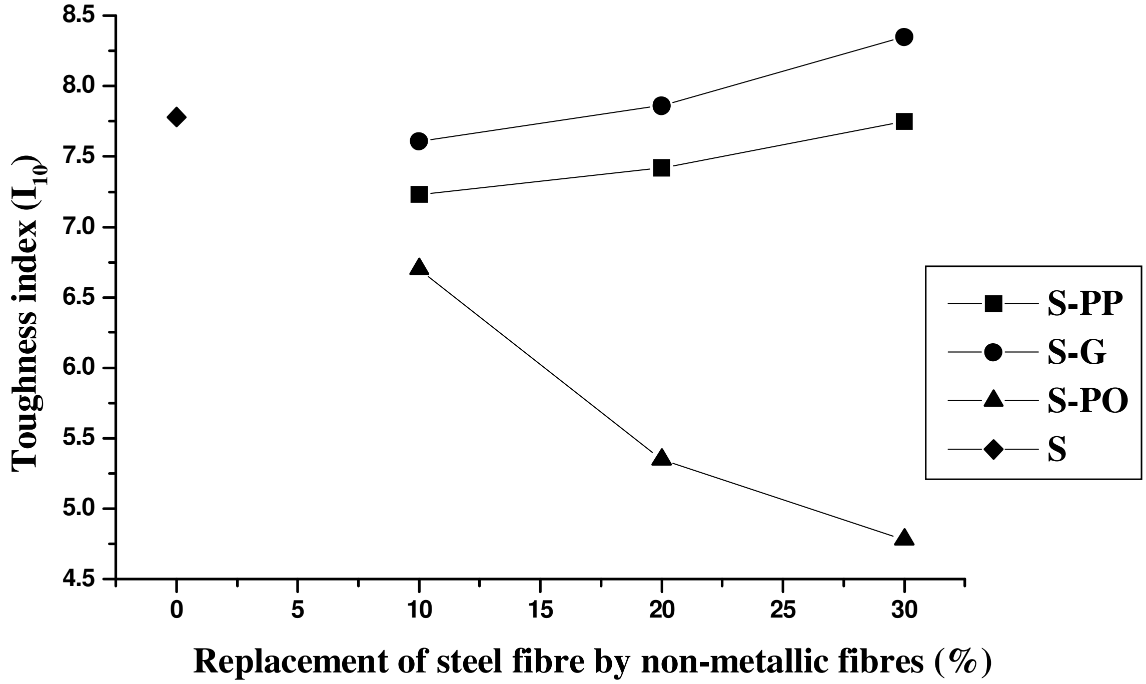

Figure 7. Plot of toughness index (I_{10}) versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

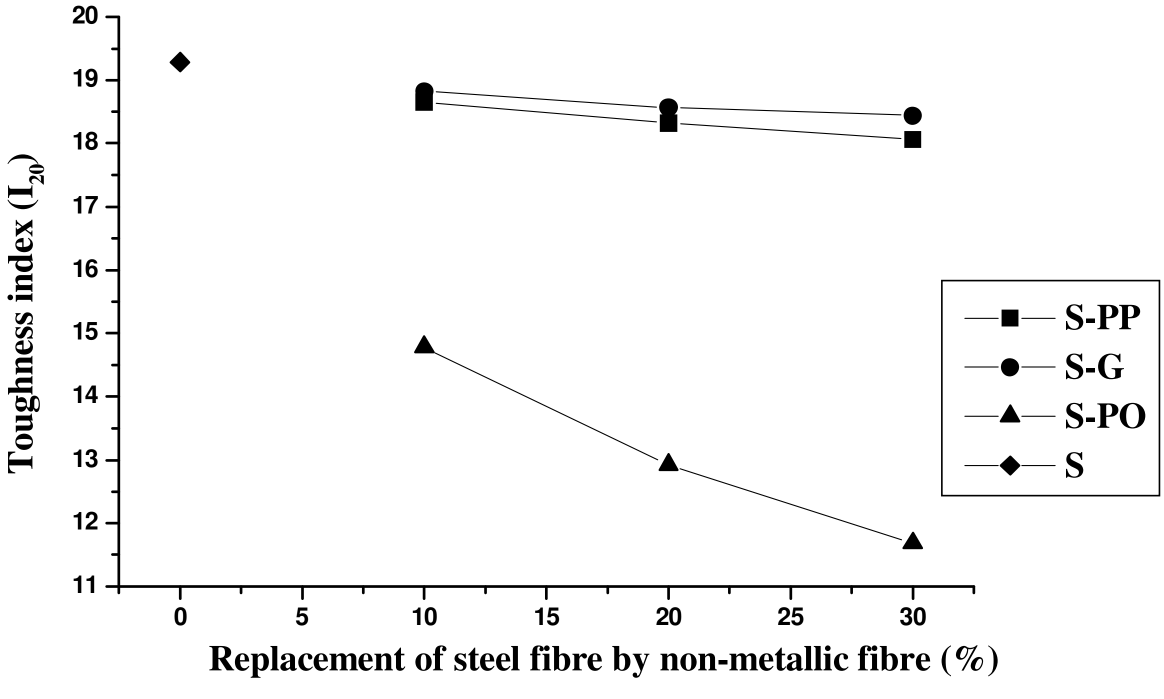

Figure 8. Plot of toughness index (I_{20}) versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

that of other hybrid fibre concretes, which reveals the fact that at high strain levels; only the steel fibres were effective in bridging the cracks, while the non-metallic fibres probably ruptured due to the high crack widths. In the case of steel-polyester fibre concretes, both the RSFs were found to be abruptly low compared to mono-steel fibre concrete and other hybrid fibre concretes due to the defects arising from poor dispersion of polyester fibres.

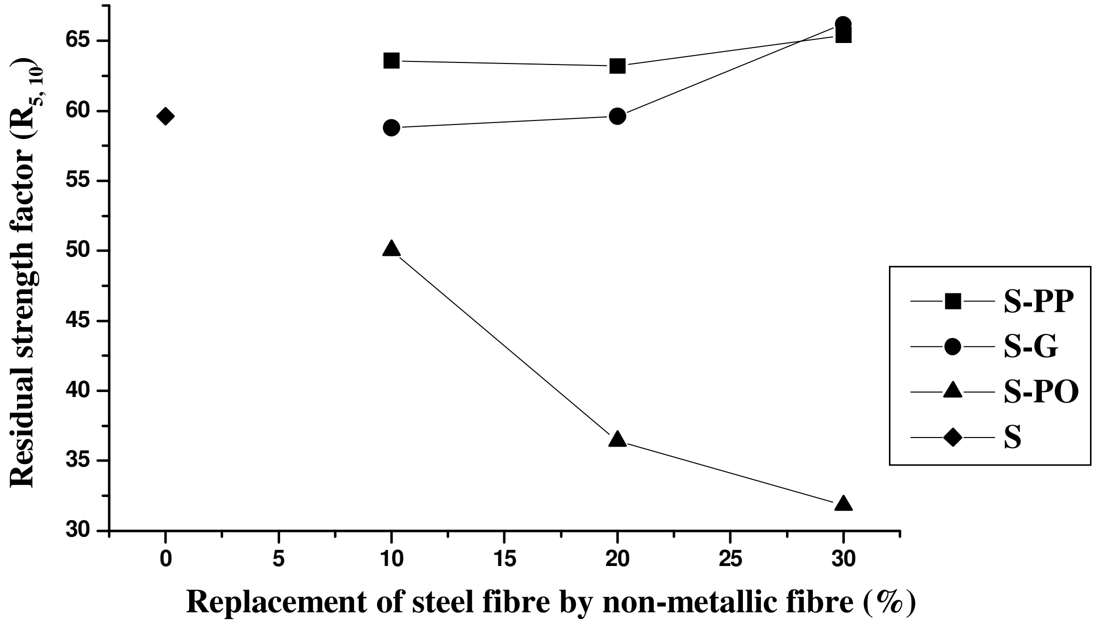

Figure 9. Plot of residual strength ($R_{5,\ 10}$) versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

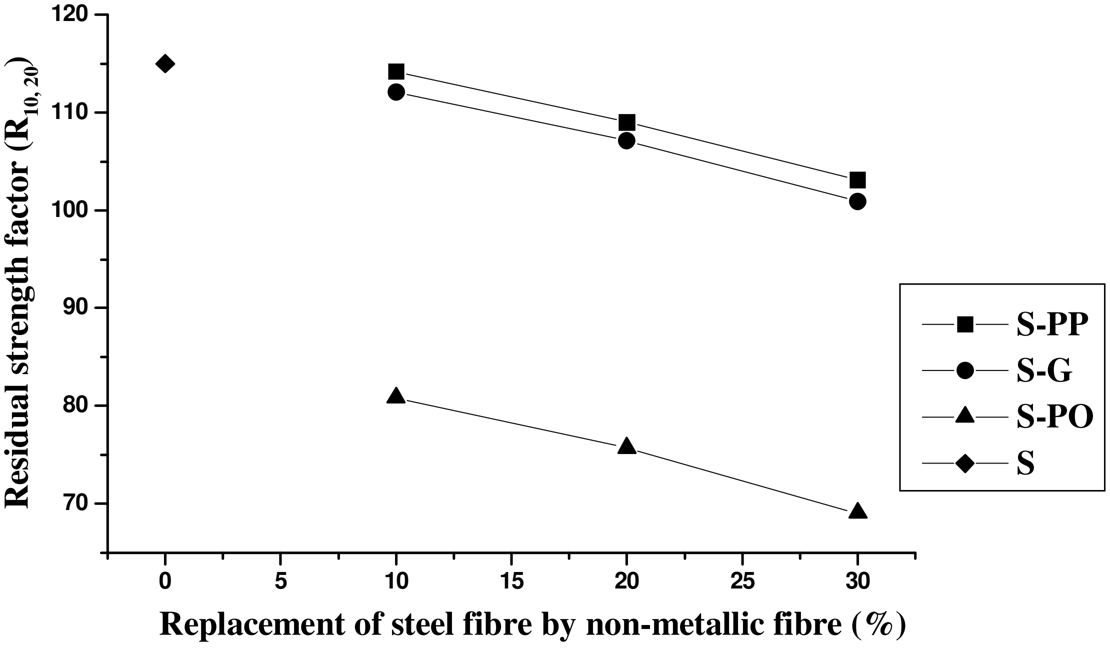

Figure 10. Plot of residual strength ($R_{10,\ 20}$) versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

Ductility

Ductility is a significant property, which characterizes the post cracking behavior of high strength concrete in terms of the deformation sustained after reaching the ultimate load. It is measured in the load deflection plot as the elongation from the point of first crack deflection (δ) to the point where there is no resistance (δ_R) offered by the concrete beam upon further loading. The calculated ductility values are given in Table 6, while the observed trends are plotted in Figure 11. The trends in Figure 11 indicate that the maximum deformation is obtained for the mono-steel fibre concrete. This is followed by the steel-glass combination, steel-polypropylene combination, and

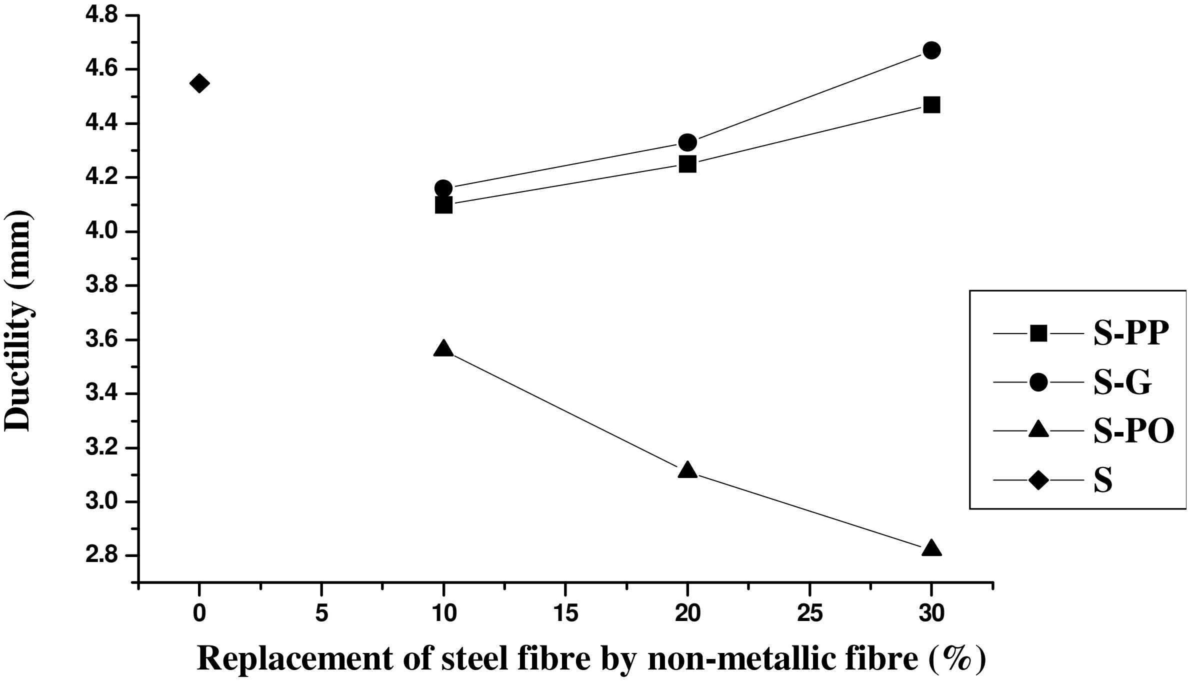

Figure 11. Plot of ductility versus replacement of steel fibre by non-metallic fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

steel-polyester combination, in that order. Moreover, for the steel-glass and steel-polypropylene combinations, the deformation is higher for a higher percentage replacement of steel fibres; this trend is similar to what was observed earlier for the toughness. The reason for this trend could be that when the steel fibres are replaced by the non-metallic fibres, the ability to bridge wide cracks at high strain levels decreases. However, when the level of replacement is high enough (~30%), the non-metallic fibres are able to contribute to the early part of the post-peak behaviour, increasing the deformation in that range (this is similar to the increase seen in the I_5 and I_{10} indices with increasing levels of steel fibre replacement). No such improvement is observed for steel-polyester combination at higher replacements of polyester fibres; on the other hand, a negative trend is seen compared to other fibre concretes as observed in Figure 11.

From the results, it is evident that the ductility depends primarily on the fibre's ability to take high levels of strain, in other words, on the stiffness of the fibre. Although the glass fibres have a reasonably high stiffness and tensile strength, they rupture at wide crack openings due to their high aspect ratio. Because of this reason, they are not able to contribute much to the ductility at the higher end of deflections. However, at high enough replacement of the steel fibres, the glass fibres are able to contribute to the ductility by controlling the thinner cracks. The same argument could be used for the polypropylene fibres; however, these fail at much lower loads, and are not able to take up too much strain because of their low stiffness.

Post crack strength (PCS)

The post crack strength determines the strength retained by the material after the ultimate load. The post crack strength for four points bending proposed by Banthia and Jean (1985) is given by:

$$PCS = (A_{post}\, L) / (D\text{-}D_p\, b_w^2) \qquad (6)$$

Where,
A_{post}-Area of post crack region (mm^2)
L - Length of the beam specimen (mm)
D - L/150 (mm)
D_p-Deflection at first crack (mm)

The calculated values of the post crack- strength are given in Table 6, while the observed trends are shown in Figure 12. The trends observed in the toughness and ductility measurements are also reflected in the PCS measurements. It can be observed from Figure 12 that the higher the replacement of steel fibres with glass or polypropylene fibres, the higher the post crack strength. At high replacement levels, the post-crack strengths for these two combinations match or better the PCS of mono-steel fibre concrete. These results can once again be explained by the suggestion that at high replacement levels of steel fibres, there is a significant contribution to the early part of the post-peak load-deflection curve from the non-metallic fibres. In the case of the steel-polyester combination, however, there is a drop in the PCS with an increase in the level of polyester fibres. This indicates

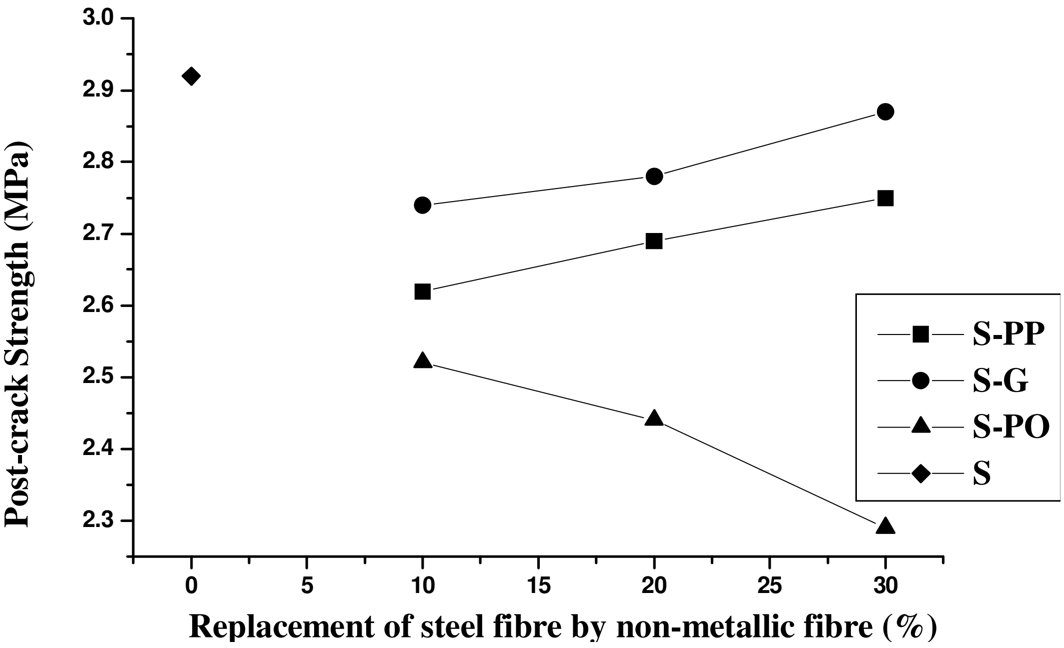

Figure 12. Plot of post crack strength versus replacement of steel fibre for various hybrid fibre concretes at total fibre volume fraction of 0.5%.

that the polyester fibres are not contributing much to the post crack behaviour, or, as said earlier, their dispersion into the concrete mixture is not proper.

Conclusions

The primary objective of this study was to evaluate the effectiveness of hybrid fibre combinations at low volume fractions in improving the post-peak behaviour of high strength concrete. Results from the study indicate the following:

i. It is possible to produce hybrid fibre concretes using glass, polyester, and polypropylene fibres in combination with steel fibres, with an enhanced ductility compared to controlled concrete without fibres.
ii. The steel-glass and steel-polypropylene hybrid combinations in concrete result in comparable levels of flexural strength, toughness, and ductility to mono-steel fibre concrete; steel-polyester combinations, however, yield a poorer composite than the mono-steel fibre concrete.
iii. The experimental observations for toughness and ductility reveal that the best performance of steel-glass and steel-polypropylene hybrid combinations is obtained at a high level of non-metallic fibre; the reason could be that at high levels of non-metallic fibres, there is significant enhancement in the early part of the post-peak behaviour.
iv. 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 of bridging smaller microcracks, could be the reasons for the enhancement in flexural properties.

A major significance of these findings is that steel fibres in concrete could be partially replaced with non-metallic fibres without compromising the ductility. This, in combination with the improved early age crack resistance that is made possible by the non-metallic fibres, make hybrid fibre combinations highly competitive as far as applications in high strength or high performance concrete are concerned.

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