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STRENGTH AND FLEXURAL TOUGHNESS OF CONCRETE REINFORCED WITH STEEL – POLYPROPYLENE HYBRID FIBRES

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ABSTRACT

Results of an investigation conducted to evaluate the strength and flexure toughness of Hybrid Fibre Reinforced Concrete (HyFRC) containing different combinations of steel and polypropylene fibres are presented. An experimental programme was planned in which beam specimens of size 100 x 100 x 500 mm were tested under four point static flexural loading to obtain the flexural strength of HyFRC. In addition, cube specimens of size 150 x 150 x 150 mm were also tested to obtain its compressive strength. The specimens incorporated steel and polypropylene fibres in the mix proportions of 100-0%, 75-25%, 50-50%, 25-75% and 0-100% by volume at a total volume fraction of 1.0%. The flexural toughness parameters were obtained using procedure laid down in ASTM C-1018 C, JCI Method, ASTM 1609/C 1609 M and Post Crack Strength (PCS) Method. The results indicate that concrete containing a fibre combination of 75% steel fibres + 25% polypropylene fibres can be adjudged as the most appropriate combination to be employed in HyFRC for compressive strength, flexural strength and flexural toughness.

Keywords: Hybrid fibre reinforced concrete; flexural strength; flexural toughness

1. INTRODUCTION

It is known that concrete is relatively a brittle material and has serious short-coming of poor toughness. Addition of randomly distributed fibres improves concrete structural characteristics viz. static flexural strength, ductility and flexural toughness etc., which depend upon fibre type, size, aspect ratio and volume fractions of the fibres used.

Recent years have seen considerable interest in the fibre hybridization – particularly combinations of metallic and non-metallic fibres. For optimal behaviour, different types of metallic and non-metallic fibres have been combined. The mechanical properties such as compressive strength, flexural strength and flexural toughness etc. of Hybrid Fibre Reinforced Concrete (HyFRC) have been investigated by different investigators. Positive synergy between the large size steel and small size polypropylene fibres was reported with

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regard to load bearing capacity of concrete by Qian and Stroeven [1]. Influence of fibre type and combinations on the crack growth resistance of steel and polypropylene fibre reinforced concrete was reported in another investigation by Banthia and Nandakumar [2]. Mechanical properties such as compressive strength, splitting tensile strength and flexural strength were compared for concrete containing different combinations of steel, carbon and polypropylene fibres at a fibre volume fraction of 0.5% [3]. It was observed concrete reinforced with the carbon-steel combination achieved highest strength. Various researchers reported the results of investigations carried out to study the flexural behaviour of concrete containing different combinations of steel, mesophase pitch based and isotropic pitch based carbon, macro and micro polypropylene fibres, glass and polyester fibres [4, 5, 6]. The results indicated that such hybridization indeed is a promising concept. Strain hardening and multiple cracking behaviour of hybrid fibre reinforced cement composites containing fly ash and different combinations of steel and polyethylene fibres were investigated [7]. The results suggested that 50% replacement of cement by fly ash is an optimum replacement for hybrid fibre composites. Two different types of polypropylene fibres i.e. monofilament and staple fibres were combined to study the mechanical properties of hybrid fibrous concrete [8]. It has been shown that the performance of hybrid fibre reinforced concrete is better than mono fibre concrete mixes. The influence of mixed aspect ratio of steel fibres on the fresh and hardened properties of fibrous concrete was reported by Mohammadi et al. [9]. The effect of polypropylene fibres and silica fume on the mechanical properties of lightweight concrete exposed to high temperature was also investigated and it was observed that the most effective parameter for the mechanical properties of lightweight fibre reinforced concrete was degree of heating and the optimum parameters for compressive strength were different from those for flexural strength [10].

2. RESEARCH SIGNIFICANCE

In the recent past, investigators attempted to enhance the mechanical properties of fibre reinforced concrete using fibre hybridization. Different types of fibres in different combinations have been employed with varying sizes of concrete specimens. Though enhancement in the mechanical properties of HyFRC has been reported through fibre hybridization, but there exists little understanding of hybrid fibre composites and the information is still scanty. Hence, this investigation was planned to study the flexural behaviour of HyFRC containing hybrids of steel and polypropylene fibres. Different proportions of steel and polypropylene fibres varying from 100% steel fibres to 100% polypropylene fibres have been investigated to evaluate the mechanical properties of HyFRC. Tests such as compressive strength and flexural strength have been conducted on concrete specimens containing different combinations of steel and polypropylene fibres. The toughness parameters of HyFRC have been evaluated as per ASTM C 1018 C [11], JCI Method [12], ASTM C 1609 M [13] and a method called Post Crack Strength (PCS) [4, 5].

3. EXPERIMENTAL PROGRAMME

The concrete mix proportion used in this investigation for casting the test specimens is shown in Table 1. Pozzolanic Portland Cement, crushed stone coarse aggregates with maximum size of 12mm and locally available river sand were used. The materials conformed to the relevant Indian Standard Specifications. Corrugated steel fibres 35mm long, 2 mm wide and 0.6 mm in thickness and homo-polymer fibrillated polypropylene fibres were used in different combinations of 100-0%, 75-25%, 50-50%, 25-75% and 0-100% by volume at a total fibre volume fraction of 1.0%. The specimen used for compressive strength tests were 150 x 150 x 150 mm cubes whereas standard prisms of size 100 x 100 x 500 mm were used for flexural strength tests. Table 2 presents the details of various fibre concrete mixes used in this investigation.

Table 1: Concrete mix proportion

Water/Cement ratio	**Sand/Cement ratio**	**Coarse aggregate/Cement ratio**
0.46	1.52	1.88

Table 2: Fibrous concrete mixes

Type of fibres	**Fibre mix proportion by volume (%)**				
	Total volume fraction, V_f = 1.0%				
Steel fibres (SF)	0	25	50	75	100
Polypropylene fibres (PPF)	100	75	50	25	0

The specimens were cast in different batches, each batch consisting of nine standard flexural test specimens and three cubes for determining the 28-day compressive strength of each mix. The specimens for compressive strength tests were cured in potable water for 28 days, whereas, the specimens for flexural strength tests were cured for 60 days. Appropriate dose of super-plasticizer was used to maintain workability. In fact, this paper forms a part of a larger investigation being conducted to investigate the flexural fatigue characteristics of concrete containing hybrids of steel and polypropylene fibres. Out of each batch of concrete, three specimens were tested in static flexure and the remaining six specimens were left for carrying out flexural fatigue tests. This paper reports the results of the static compressive strength and static flexural strength tests and the results of the flexural fatigue tests shall be reported in a separate paper.

The compressive strength tests were conducted on concrete cubes in a 2000 kN Universal Testing Machine whereas, the flexural strength tests were conducted on a 100 kN servo-controlled actuator.

4. RESULTS AND DISCUSSION

4.1 Compressive strength test results

The results of the compressive strength test conducted on HyFRC containing different combinations of steel and polypropylene fibres are presented in Table 3 and Figure 1. The 28 days compressive strength of plain concrete is also shown in Table 3 and Figure 1 for reference. It is observed that the with the introduction of 100% polypropylene fibres to the plain concrete, the compressive strength drops to 35.40 MPa from 40.15 MPa resulting in approximately 13% reduction. Banthia and Soleimani [4] also reported approximately 13% reduction in compressive strength of concrete containing 100% polypropylene fibres as compared to that of plain concrete. However, an increase in the compressive strength of fibrous concrete is observed with the addition of steel fibres to the mix and maximum compressive strength is obtained for concrete containing 75% steel fibres+25% polypropylene fibres. In general, there is an increase in compressive strength varying from 6% to 18% on addition of fibres to concrete and the optimum fibre combination is 75% steel fibres + 25% polypropylene fibres for which the maximum increase in compressive strength of 18% over plain concrete is observed. Further, it can also be seen that the compressive strength of concrete mix containing 50% steel fibres + 50% polypropylene fibres is higher than that of concrete mix containing 100% steel fibres. The percentage increase/decrease in compressive strength of HyFRC over plain concrete is presented in Figure 2.

Table 3: Compressive strength test results for HyFRC

Fibre mix proportion by volume (%)		Fibre volume fraction	28 Days compressive strength (MPa)*				
			Cube compression				%Age increase
SF	PPF		Batch 1	Batch 2	Batch 3	Average	
--	--	0.0	39.70	40.50	--	40.15#	0
0	100	1.0	35.05	35.55	34.75	35.10	-13
25	75	1.0	37.90	39.60	39.95	39.20	-2
50	50	1.0	45.70	46.20	44.85	45.60	14
75	25	1.0	47.60	49.60	45.05	47.40	18
100	0	1.0	41.40	44.95	41.65	42.65	6

** Average of Three Specimens*
 # Average of Two Batches

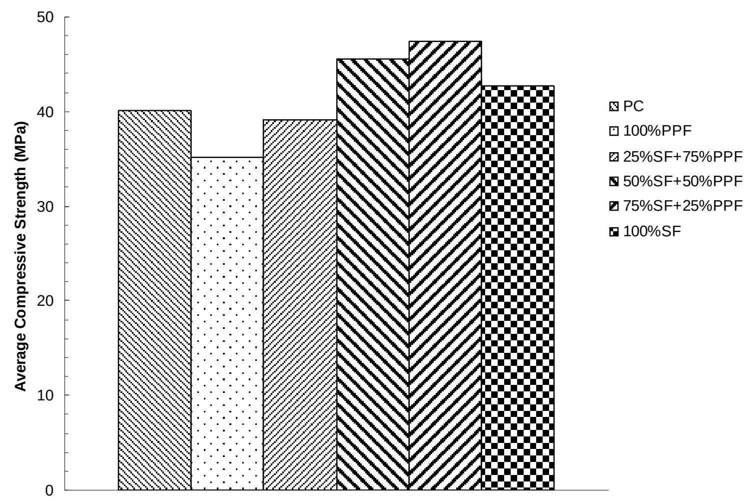

Figure 1. Compressive strength of HyFRC for different fibre combinations

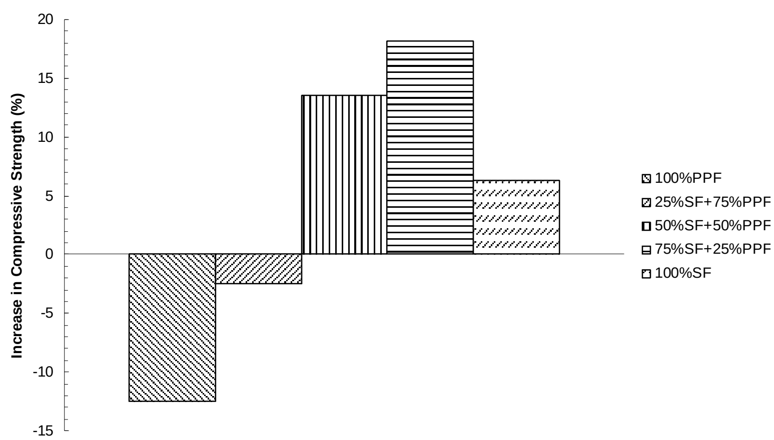

Figure 2. Percentage increase in compressive strength of HyFRC over that of plain concrete

4.2 Flexural strength test results

The flexural strength results for HyFRC containing different combinations of steel and polypropylene fibres are presented in Table 4 and Figure 3. The flexural strength of plain concrete is also listed for reference and comparison. The percentage increase/decrease of flexural strength of fibrous concrete with respect to plain concrete is presented in Figure 4. It can be seen that in general, like compressive strength, the flexural strength of concrete containing 100% polypropylene fibres is less than that of the plain concrete. There is a drop of approximately 7% in the flexural strength of concrete containing 100% polypropylene fibres as compared to that of plain concrete. Banthia and Soleimani [4] reported approximately 11% reduction in flexural strength of concrete containing 100% polypropylene fibres as compared to that of plain concrete. With gradual replacement of polypropylene fibres with steel fibres, an increase in the flexural strength is observed up to a fibre combination of 75% steel fibres + 25% polypropylene fibres. With further replacement of polypropylene fibres with steel fibres i.e. for concrete containing 100% steel fibres, a decrease in flexural strength is observed. The increase in flexural strength taken as average of three batches of fibrous concrete containing different combinations of steel and polypropylene fibres varied from 40% to 80%, showing an increase of 42% for HyFRC with 25% steel fibres + 75% polypropylene fibres; 55% for 50% steel fibres + 50% polypropylene fibres; 80% for concrete containing 75% steel fibres + 25% polypropylene fibres and 40% for concrete containing 100% steel fibres. Thus the optimum fibre combination for maximum flexural strength is 75% steel fibres + 25% polypropylene fibres as obtained in this investigation.

Table 4: Flexural strength test results for HyFRC

Fibre mix proportion by volume (%)		**Fibre volume fraction**	**Flexural strength (MPa)***				
SF	**PPF**		**Batch 1**	**Batch 2**	**Batch 3**	**Average**	**% Increase**
---	---	0.0	4.20	4.20	---	4.20	--
0	100	1.0	3.30	3.60	4.80#	3.90	-7
25	75	1.0	6.05	6.00	5.80	5.95	42
50	50	1.0	6.70	6.40#	6.50#	6.50	55
75	25	1.0	7.65	7.40#	7.70	7.60	80
100	0	1.0	5.60#	5.60	6.40	5.90	40

* ***Average of 3 Specimens***
\# ***Average of 2 Specimens***

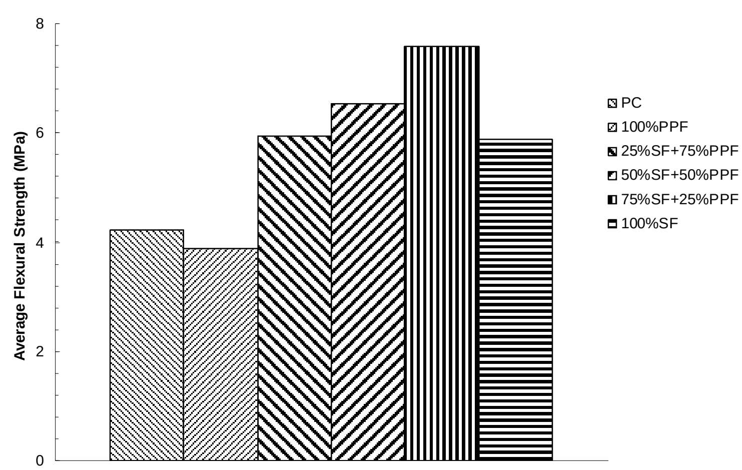

Figure 3. Flexural strength of HyFRC for different fibre combinations

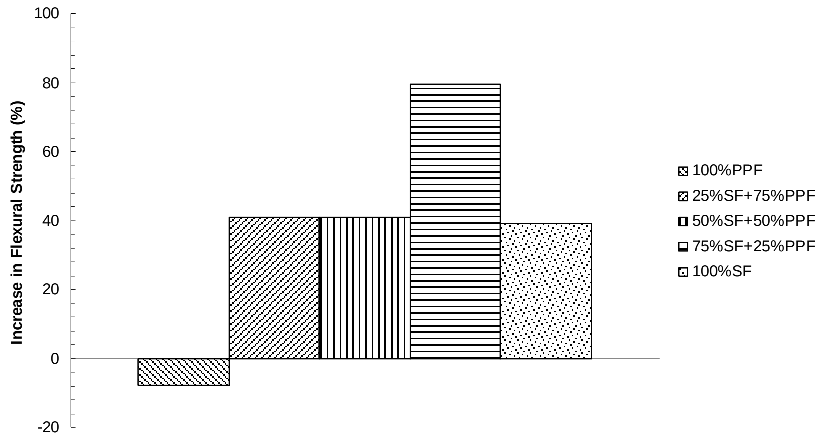

Figure 4. Percentage increase in flexural strength of HyFRC over that of plain concrete

Typical load-deflection curves obtained in this investigation for concrete containing different combinations of fibres are presented in Figure 5. The average peak loads and corresponding deflections for fibrous concrete with different combinations of both types of fibres are presented in Table 5. The peak load and corresponding centre point deflection for plain concrete are also presented for reference. The increase in centre-point deflection corresponding to peak load as compared to plain concrete varied from 31% to 85% - with an increase of 31% for 100% polypropylene fibre; 50% for 25% steel + 75% polypropylene fibre; 85% for 50% steel fibre + 50% polypropylene fibre; 84% for 75% steel fibre + 25% polypropylene fibre and; 23% for 100% steel fibres. The maximum increase in the value of centre-point deflection was obtained for 50% steel fibre + 50% polypropylene fibres while the minimum increase in the centre point deflection over plain concrete was for 100% steel fibres. Figure 6 shows the variation of peak load and first crack load with the percentage of steel fibres in the concrete mix.

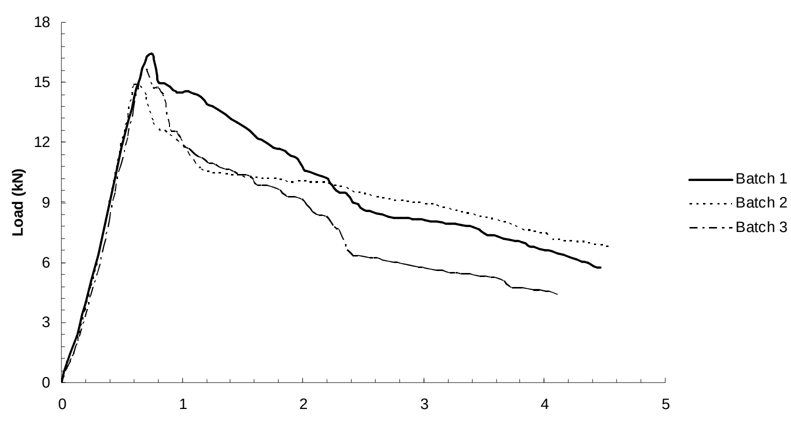

Figure 5. Load-deflection curves for HyFRC, 75% steel fibres + 25% polypropylene fibres

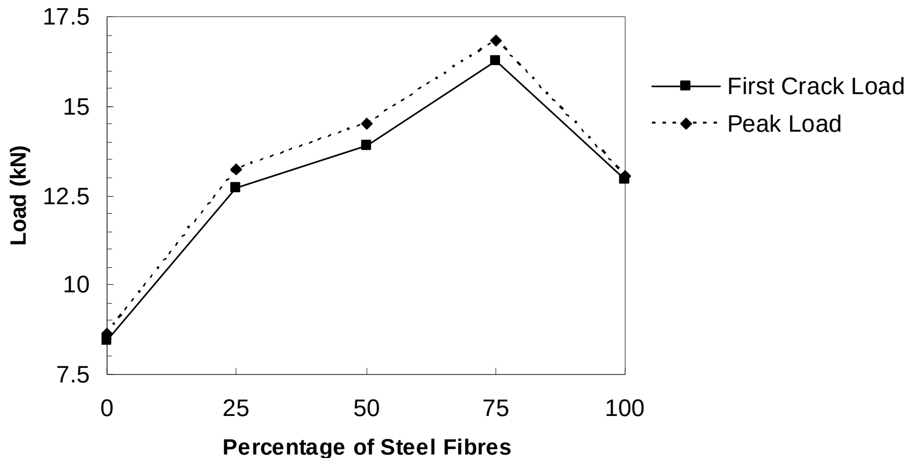

Figure 6. Average first crack loads and peak loads vs. steel fibre content in concrete mix

Table 5: Average peak loads and corresponding deflections

Fibre mix proportion by volume (%)		Fibre volume fraction	Maximum load and corresponding deflection*	
SF	PPF		Deflection (mm)	Load (kN)
---	---	0	0.402	9.30
0	100	1.0#	0.528	8.64
25	75	1.0	0.601	13.22
50	50	1.0&	0.745	14.53
75	25	1.0#	0.740	16.82
100	0	1.0#	0.493	13.04

** Test conducted on 3 batches (3 Samples each)*
 # 1 batch containing 2 Samples
& 2 batches containing 2 Samples

4.3 Flexural toughness

Concrete due to its brittle behaviour has little ability to resist tensile stresses and strains. Discontinuous fibres are added to improve energy absorption capacity and to provide improved resistance to cracking. Thus flexural toughness is an important parameter in assessing the influence of fibres on the post-peak behaviour of fibre reinforced concrete. A number of methods have been developed to obtain the flexural toughness and performance of fibre reinforced concrete. The flexural toughness parameters have been obtained using various methods [11-13]. In addition, a method based on Post Crack Strength (PCS) proposed by Banthia and Sappakittipakorn [5] has also been used to evaluate the flexural toughness of fibrous concrete containing different combinations of steel and polypropylene fibres.

Table 6 presents various toughness parameters such as I_5, $I_{10,}$ I_{10}/I_5, $R_{5,\ 10}$ obtained by ASTM C 1018 and T_{JCI}, S_{JCI} obtained using JCI method for HyFRC containing different combinations of steel and polypropylene fibres. The toughness index for plain concrete in ASTM C 1018 Method is taken as 1.0 because plain concrete flexural test specimens fail immediately after the formation of first crack. The flexural performance parameters such as P_{600}, P_{150}, $f_{600,}$ f_{150}, T_{600} and T_{150} for fibrous concrete as obtained using ASTM C 1609/C 1609 M are presented in Table 7 for HyFRC containing different combinations of steel and polypropylene fibres.

It can be observed from Table 6 that the best performance is given by concrete containing 75% steel fibres+25% polypropylene fibres. The highest values of T_{JCI} and S_{JCI} are 31.64 kN-mm and 4.74 MPa respectively for concrete with 75% steel fibres + 25% polypropylene fibres, whereas, the lowest values of 7.57 kN-mm and 1.13 MPa are obtained for concrete containing 100% polypropylene fibres. Similarly, the highest values of the parameters obtained using ASTM C 1018 C are for concrete with 75% steel fibres + 25% polypropylene fibres. It can also be concluded from Table 6 that in general, concrete containing hybrid fibres i.e. combinations of steel and polypropylene fibres gave better performance as compared to concrete containing single type of fibres – be 100% steel or 100% polypropylene fibres. The variation of indices I_5 and I_{10} with the increase in percentage of steel fibres in the concrete mix is shown in Figure 7.

Table 6: Average flexural toughness indices using JCI and ASTM C-1018

Fibre mix proportion by volume (%)		**Fibre volume fraction**	**Toughness indices***						
			JCI METHOD		**ASTM C-1018**				
SF	**PPF**		**T_{JCI} (kN-mm)**	**S_{JCI} (MPa)**	**$T_{F.C.}$ (kN-mm)**	**I_5**	**I_{10}**	**I_{10}/I_5**	**$R_{5,10}$**
0	100	1.0#	7.57	1.13	2.34	2.90	4.78	1.65	37.40
25	75	1.0	20.63	3.09	3.82	3.38	5.22	1.54	37.42
50	50	1.0&	25.32	3.80	4.49	3.24	5.15	1.59	38.22
75	25	1.0#	31.62	4.74	5.59	3.84	6.32	1.65	49.65
100	0	1.0#	22.02	3.30	3.13	3.40	4.96	1.46	31.17

** Test conducted on 3 batches (3 Samples each)*
 # 1 batch containing 2 Samples
& 2 batches containing 2 Samples

Table 7: Average flexural toughness indices using ASTM C-1609

Fibre Mix proportion by volume (%)		**Fibre volume fraction**	**Toughness indices***					
			ASTM C-1609					
SF	**PPF**		**P_{600} (kN)**	**P_{150} (kN)**	**f_{600} (MPa)**	**f_{150} (MPa)**	**T_{600} (Joules)**	**T_{150} (Joules)**
0	100	1.0#	2.91	1.33	1.30	0.60	3.61	7.57
25	75	1.0	10.32	5.37	4.64	2.41	5.30	20.63
50	50	1.0&	12.23	6.10	5.50	2.74	4.98	25.32
75	25	1.0#	16.40	8.07	7.38	3.63	6.47	31.62
100	0	1.0#	12.52	2.93	5.63	1.31	4.04	22.02

** Test conducted on 3 batches (3 Samples each)*
 # 1 batch containing 2 Samples
& 2 batches containing 2 Samples

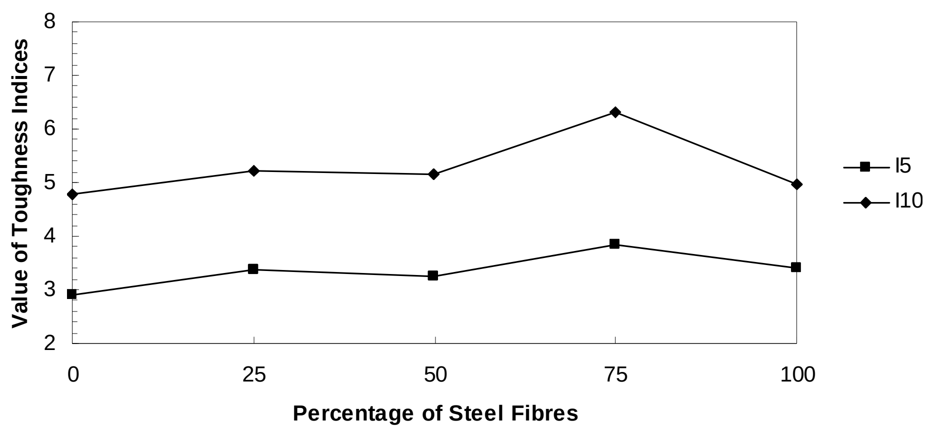

Figure 7. Average values of I_5 and I_{10} vs. steel fibre content in concrete mix

As is evident from Table 7, the residual strengths f_{600}, f_{150} and the toughness parameters T_{600} and T_{150} show more or less similar trends as presented by toughness parameters obtained by the other two methods discussed in the preceding sections. The lowest values of toughness T_{600} and T_{150} i.e. 3.61 Joules and 7.57 Joules respectively are shown by concrete containing 100% polypropylene fibres. As the polypropylene fibres are partially replaced with steel fibres, an increase in the values of both T_{600} and T_{150} is observed which continues up to a fibre combination of 75% steel fibres + 25% polypropylene fibres which records highest values of the toughness parameters. Further replacement of polypropylene fibres with steel fibres i.e. for concrete containing 100% steel fibres, a decrease in the values of toughness parameters is observed.

The load–deflection curves as obtained in this investigation for HyFRC containing different combinations of fibres have also been analysed by Post Crack Strength (PCS) method as reported by various researchers [4, 5]. It is a method of converting a load-deflection curve into an equivalent flexural strength curve. The method as demonstrated in Figure 8, locates the peak load and divides the curve into two regions i.e. pre peak and post peak. In the post peak region, the points are located corresponding to deflections coinciding with various fractions of the span. For a beam with width b and depth h, the Post Crack Strength (PCS) at a deflection L/m is given by the following expression [5]:

$$PCS = \frac{E_{post,m}}{\left(\frac{l}{m} - \delta_{peak}\right)} x \left(\frac{L}{bxh^2}\right) \tag{1}$$

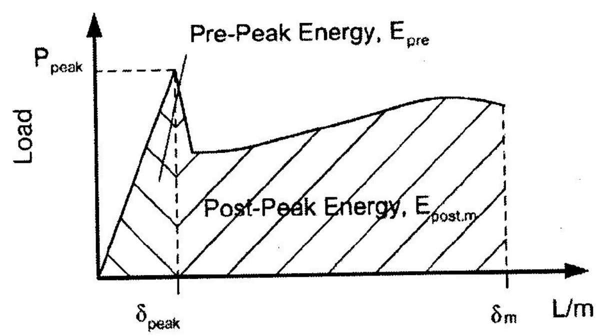

Figure 8. Post crack strength (PCS) analysis on a fibrous concrete beam

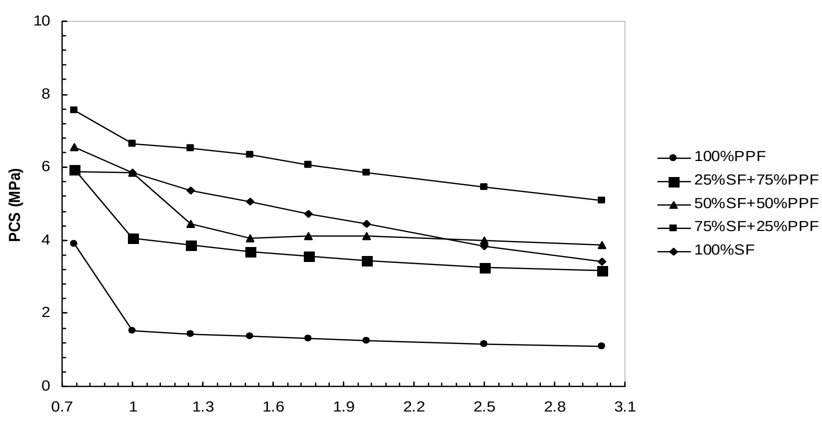

Figure 9. PCS values for HyFRC containing different combinations of steel and polypropylene fibres

The load-deflection curves obtained in this investigation have been analysed using the said method and a plot of the PCS with respect to L/m ratios for different mix combinations of fibres used is shown in Figure 9. It is observed from Figure 9 that concrete containing 100% polypropylene fibres showed lowest PCS values. The PCS values increased significantly with 25% replacement of polypropylene fibres by the steel fibres. Howvere, he highest PCS values are obtained for concrete containing 75% steel fibres + 25% polypropylene fibres which appear to be a promising combination.

5. CONCLUSION

Properties, such as compressive strength, flexural strength and flexural toughness of HyFRC containing different combinations of steel and polypropylene fibres have been investigated. The flexural toughness indices/parameters were obtained from the load – deflection curves as per procedure laid down in ASTM C 1018, JCI Method and ASTM C 1609/C 1609 M. The load-deflection curves have also been analysed using PCS technique. A maximum increase in compressive strength of the order of 18% over plain concrete was observed in case of concrete containing 75% steel fibres + 25% polypropylene fibres. In case of static flexural strength tests, a maximum increase in flexural strength of the order of 80%, centre point deflection corresponding to peak load of the order of 84% was observed for HyFRC with 75% steel fibres + 25% polypropylene fibres. The results obtained in this investigation indicate that, in terms of flexural toughness, concrete with fibre combination of 75% steel fibres + 25% polypropylene fibres gives the best performance. Increase of fibre availability in the hybrid fibre system due to low density non-metallic fibres in combination of steel fibres could be the reason for the enhanced flexural toughness of the HyFRC mix.

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