Studies on Toughness of Hybrid Fibre-Reinforced Cementitious Composite Beam

Abstract

Research works over the past three decades have clearly established the potential use of different fibre reinforcement for improving the flexural capacity as well as toughness of reinforced concrete members. The addition of fibres also helps to reduce the problems of congestion due to flexure and shear reinforcement at critical sections such as beam-column junctions. In the present study, thirty six numbers of fibre reinforced concrete prisms have been tested under quasi-static load according to ASTM C1609. Two types of steel fibres with hooked-end and two types of polymer fibres, namely polypropylene and polyester have been used. Different combinations of fibres and their volume fractions have been tried to arrive at the best possible combination from the point of view of toughness. The results of test on hybrid fibre reinforced cementitious composite beams show that though there is not much improvement in ultimate load carrying capacity; but there is tremendous change in ultimate displacement even after the first crack. The hybrid fibre reinforced cementitious composite beams have exhibited 10 to 15 times enhancement in toughness as compared to a similar plain concrete beam till failure. Since the results of testing show enhanced ductile behaviour before collapse of a structural element, appropriate combination of hybrid FRC (HyFRC) are strongly recommended for practical usage.

Keywords: Toughness, Concrete, HyFRC, Macro Fibre, Micro Fibre

1. Introduction

Steel fibres and synthetic polymer fibres, typically made of polypropylene and polyester, have been used along with the basic constituents for the preparation of concrete and are observed to significantly improve the displacement till failure of RC beams as well as modified the failure behaviour. In fibre reinforced concrete (FRC), fibres can be effective in arresting cracks at both macro and micro level. It is known that failure in concrete is gradual, where the pre-existing cracks grow and eventually join together to form macro crack. A macro crack propagates at a suitable rate until it attains condition of unsuitable propagation and a rapid fracture is precipitated. A combination of steel and synthetic fibres have been used by researchers, where steel fibres are observed as effective for arresting macro-crack while synthetic fibres are found as good for arresting micro-crack.

The first-peak strength characterizes the flexural behaviour of the concrete specimen up to the onset of cracking, while residual strengths at specified deflections characterize the residual capacity after cracking. Specimen toughness is a measure of the energy absorption capacity of the test specimen. Fiber-reinforced concrete is influenced in different ways by the amount and type of fibers in the concrete. In some cases, fibers may increase the residual load and toughness capacity at specified deflections while producing a first-peak strength equal to or only slightly greater than the flexural strength of the concrete without fibers. In other cases, fibers may significantly increase the first-peak and peak strengths while affecting a relatively small increase in residual load capacity and specimen toughness at specified deflections. Load-displacement data are drawn and the areas under load-displacement curve are determined to get toughness of the fibre reinforced concrete specimens.

Failure pattern of plain concrete in tension is very brittle. Addition of fibers in the concrete leads to the enhancement of tensile strength. Fibers in concrete arrest the cracks in concrete and shares some load in tension. Thus addition of fibers in concrete enhances not only the compressive strength, tensile strength but also fatigue and toughness [Bindiganavile and Banthia (2001)]. Quantity, type of fibers and combination of both play most important role in the enhancement of the properties of the concrete. There are some other factors like aspect ratio of fiber, shape of the fibers and workability of FRC are equally important to get improved behaviour of the concrete. A brief literature review has been carried out to get the appropriate quantity and types of fiber to be used for research. Table-1 shows brief summary of the literature survey carried out for the research work presented in this paper.

In the presented study, two types of steel fibres with hooked-end and two types of polymer fibres, namely Polypropylene and Polyester have been used for the preparation of beams. Different combinations of fibres and their volume fractions have been tried to arrive at the best possible combination from the point of view of toughness. Load-displacement plot shows enhancement in ductility of the beam with fibre reinforcement, which has otherwise exhibited a brittle failure in plain concrete.

Table-1: Brief details of studies using HyFRC.

Reference	Fibers Used	Important observations
Walton and Majumdar (1975)	PP, G, Nylon , As, C	Modulus of rupture, impact strength and tensile strength of FRC with different volume fraction of different types of fibers (organic and inorganic) were studied and improvements were observed.
Banthia and Trottier (1995)	Steel	Toughness characteristics of FRC using different shaped steel fibers were studied and result showed that fibers having deformations at the ends appeared to be more efficient that those with deformations over the entire length.
Qian and Stroeven (2000)	PP, Steel	Compressive and modulus of rupture of HyFRC were evaluated and result showed that 0.15% doze of the PP by volume fraction to be optimum to get good toughness and synergy with steel
Bindiganavile and Banthia (2001)	PP, Polyolefin, Steel	Flexural toughness under quasi-static and impact loading were evaluated and observed that polymer fibers were better than steel fibers in terms of resistance to impact load
Banthia and Nandakumar(2003)	PP, Steel	Use of PP enhanced the performance of the deformed steel fiber, where study was carried out for crack growth in HyFRC
Banthia and Soleimani(2005)	Steel, C, PP	Toughness characteristics and PCS parameter were studied for HyFRC and introduced a new approach for finding toughness of HyFRC based on PCS
Altoubat et al(2009)	PP, Polyethylene	Shear behaviour of beam without stirrups but with FRC were studied. Addition of micro-synthetic fiber with 1.0% volume fraction increased the ultimate shear strength of the slender beams by 30%
Blunt and Ostertag (2009)	Steel, PVA	Optimum value for workability and deflection hardening properties of HyFRC were studied
Greenough and Nehdi(2009)	PP, Steel	Shear behaviour of slender beam having FRC were studied and result showed that addition of fibers by more than 1% could increase the shear capacity by 128%
Mohankumar and Bangaruchandran (2009)	Steel, Polyolefin	Improvement in ductility and energy absorption capacity of beam having HyFRC were observed, where optimum doze of steel to polyolefin was found as 0.6:0.4.
Jiang and Banthia (2010)	PP	Size effect on toughness of FRC using two different types of PP fibers were studied and concluded that the toughness of specimen to be dependent on the size of the specimen tested.

Note: PP = polypropylene, G = Glass; As = Asbestos; C = Carbon; PVA = Polyvinyl Alcohol.

2. Experimental Programme

2.1 Materials and Mixtures

The concrete mix used for all the specimens are M30 having a composition as given in Table 2. The amount and /or type of fibers have been varied in these mixtures along with required amount of plasticizer to get proper workability.

Steel fiber and synthetic polymer fiber (polypropylene and polyester) have been used in the mixtures of concrete. Table 3 shows detail specifications of the fibers used for investigation. Further, super plasticizer (Complast^R SP430-G8) has been used in fiber reinforced concrete to get proper workability of the concrete.

Table-2: Details of ingredients of Concrete.

Constituent	Description
Cement	PPC, 53 Grade
Coarse Aggregate	0.65 (16 MSA) : 0.35 (10 MSA)
Fine Aggregate	2.36 MSA
Mix Design	1: 1.84 : 3.18
Water Cement Ratio	0.59

Table-3: Technical Details of Fibers used as admixtures.

Types of Fibers	**Product Name**	**Length (mm)**	**Dia. (mm)**	**Shape**	**Specific Gravity**	**Tensile Strength(MPa)**
Polyester	Recron 3S	12,18	0.03 - 0.035	Triangular cross-section	1.36 - 1.38	400 - 500
Polypropylene	Recron 3S	12	0.03 - 0.035	Triangular cross-section	0.91	400 - 500
Steel	Dramix	60	0.75	Hooked End	7.8	1225
Steel	Dramix	35	0.55	Hooked End	7.8	1100

2.2 Specimen

Thirty six numbers of specimens have been cast for the investigation of toughness of the HyFRC element having different types of fibers with different volume fraction. Twelve different combinations of the mixtures have been considered in the present investigation with three samples for each combination. Table-4 shows volume fraction and type of fibers used for each combination undertaken for research. Flexural toughness test has been carried out as per ASTM C1018 and ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete. Concrete beams of size 150mm × 150mm × 700mm have been used. The actual experimental set-up is as shown in Fig. 1 and a schematic representation is shown in Fig. 2. Span considered for testing of the beam specimen is 600 mm. Concrete specimens have been tested, where the loading of the specimen has been displacement controlled. The area under the load-displacement curve was used to evaluate the total strain energy stored / toughness of the specimen.

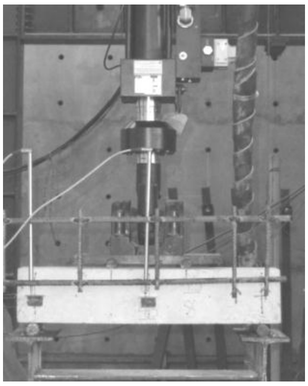

Fig. 1: Experimental set-up

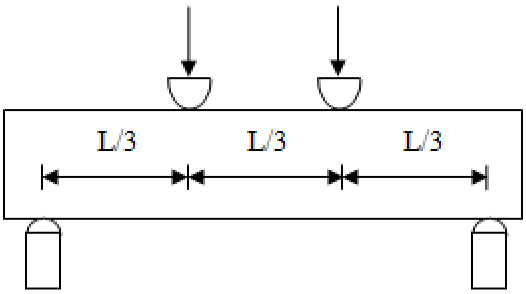

Fig. 2: Schematic view of the test set-up

3. Results and Discussion

Specimens made with different combinations of the HyFRC have been tested. Three specimens have been considered for each combination. Some of the typical load-displacement plots are shown in Fig. 3-6. The area under the load displacement curves have been evaluated as a measure of toughness. The result presented in Table 4 (last column) is the average of the three specimens under each combination. However, for better representation of the results, all the twelve combinations have been grouped under five cases as detailed below:

Case 1: Set of results of Plain Concrete and Only Steel fibers
Case 2: Set of results of HyFRC containing Polypropylene fibers 0.15 by volume fraction (%)
Case 3: Set of results of HyFRC containing Polypropylene fibers 0.20 by volume fraction (%)
Case 4: Set of results of HyFRC containing Polyester fibers 0.15 by volume fraction (%)
Case 5: Set of results of HyFRC containing Polyester fibers 0.20 by volume fraction (%)

Table-4: Result table of test of Cementitious Composite Beam Specimen

No. of Combination 4.	**Types of Fibers (Volume Fraction, %)**				**Total Volume Fraction (%)**	**Average Toughness KN.mm**
	SF1	**SF2**	**PP**	**PE**		
PL[1]	-	-	-	-	-	24.949
SF[2]	0.5	0.5	-	-	1	250.039
1	0.4	0.4	0.15	-	0.95	361.291
2	0.4	0.4	0.2	-	1	280.991
3	0.5	0.5	0.15	-	1.15	389.317
4	0.5	0.5	0.2	-	1.2	321.982
5	0.6	0.6	0.15	-	1.35	364.467
6	0.4	0.4	-	0.15	0.95	306.551
7	0.4	0.4	-	0.2	1	307.375
8	0.5	0.5	-	0.15	1.15	298.071
9	0.5	0.5	-	0.2	1.2	305.843
10	0.6	0.6	-	0.15	1.35	300.253

PL[1] = Plain Concrete, SF[2] = Steel Fiber

It may be observed from the Fig. 7 and 8 that the toughness of the specimen changes as volume fraction of the hybrid fibers varies in concrete. Case 2 and Case 3 show optimum dosage of fibers of about 1.15 to 2% of total volume fraction having micro fiber dosage of 0.15 and / or 0.2 % of total volume fraction. However, Case 4 and Case 5 results show a different trend. The study with twelve combinations has clearly shown that the best toughness can be achieved with a combination of steel fibers (two different sizes with 0.5 and 0.5 total volume fraction (%)) and polypropylene (with 0.15 by total volume fraction (%)). Though the variation in toughness for different volume fraction of polyester fibers is not significant, 1.15% total volume fraction has not been found as good as has been found for combination with polypropylene fibers. The enhancement in toughness has been found to be 10 to 15 times that of the plain concrete specimen due to the addition of hybrid fibers in the concrete.

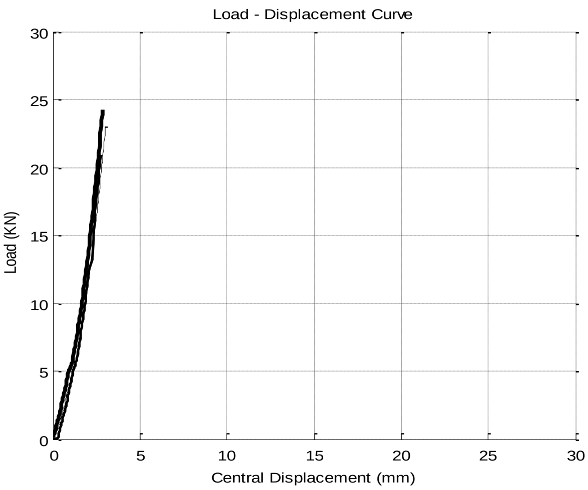

Fig. 3: Load – Displacement Curve for PL[1]

Fig. 4: Load – Displacement Curve for SF[2]

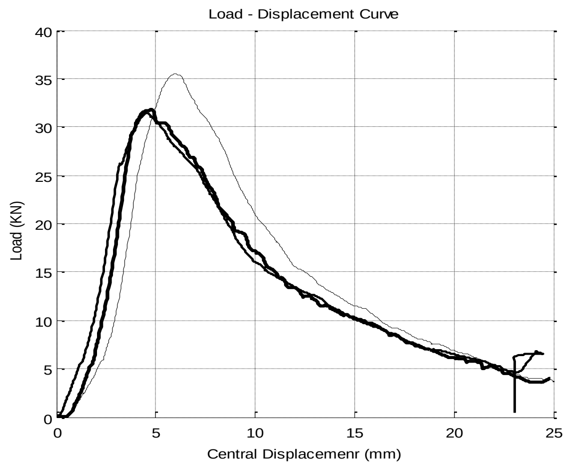

Fig.5: Load–Displacement Curve for Combination 3

Fig.6 : Load–Displacement Curve for Combination 7

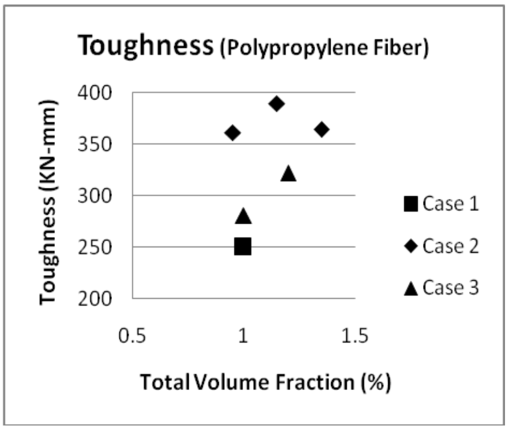

Fig. 7: Toughness for Case 1, Case 2 & Case 3

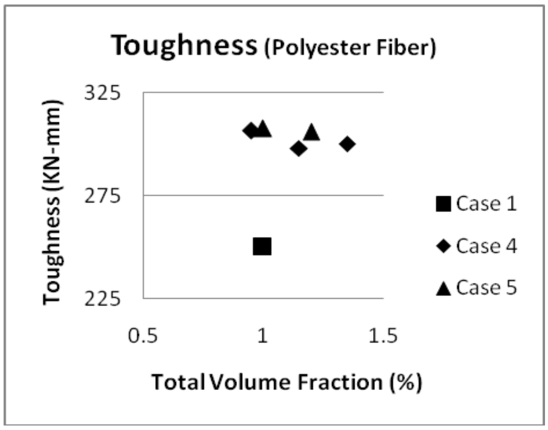

Fig. 8: Toughness for Case 1, Case 4 & Case 5

Comparisons of Fig. 3 with Fig. 4-6 show a clear enhancement in ductility of the beam, which has shown a typical brittle failure in plain concrete (fig. 3). Though there is not much change in ultimate load; but there is tremendous change in ultimate displacement even after the first crack. Recession parts of Fig. 4-6 show increase in strain energy storing capacity. Fig.9 shows a typical brittle mode of failure of unreinforced concrete prism. However, ductile mode of failure may be observed from Fig. 10-12, where the load transfer mechanism from concrete to micro-fibers to macro-fiber can also be observed. Concrete cracks first followed by failure of micro-fibers (i.e. polymer fibers) and finally macro-fibers (i.e. steel fibers) lose their load supporting ability due to pull out.

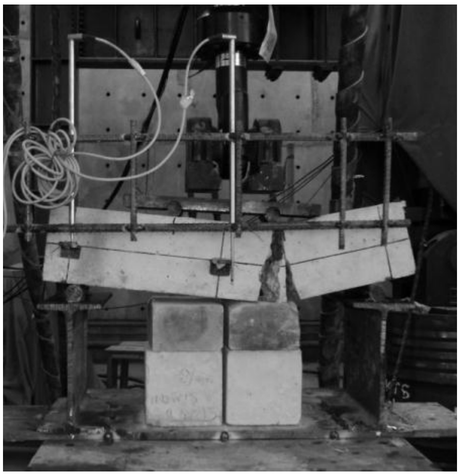

Fig.9: Failure of concrete Beam without fibers

Fig.10: Growth of Crack pattern and failure of Micro-Fibers (i.e. Polymer fiber)

Fig. 11: Failure of polymer fibers as well as pull out effect of steel fibers

Fig.12: Zoomed view of pull out of Steel fibers after full development of crack

5. Conclusion

HyFRC outperformed FRC in terms of toughness, while the flexural load carrying capacity was only marginally increased. In general, specimens made of HyFRC showed substantial (10 to 15 times for specimens tested) enhancement in energy absorption capacity while these were tested under flexural quasi-static loading. Hybrid FRC comprising of two basic types of fibres i.e. Steel Fibers and Synthetic Polymer Fibers (polypropylene, polyester) performed extraordinary, especially combination 3 as compared to all other combinations. Use of steel fiber arrested macro-cracks in concrete, while polypropylene fiber arrested micro-crack. Result of all the testing using fibres in concrete showed substantial improvement in ultimate displacement and thus change in failure pattern of these specimens could be observed.

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6. Reference

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