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Influence of Fiber Hybridization on Strength and Toughness of RC Beams

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Abstract

This paper focuses on the experimental investigation designed to study the behavior of hybrid fiber-reinforced concrete (HFRC) beams under flexure and impact loading. The addition of fibers to concrete can improve a number of its properties. For optimal response, different types of fibers may be suitably combined to produce HFRC. Optimized combinations of different fiber types in concrete can produce a composite with better engineering properties than that with only one type. The study compared the mechanical properties of fresh and hardened HFRC, Steel Fiber Reinforced Concrete (SFRC), and conventional concrete to arrive at the optimum fiber content for improved behavior of concrete by testing 135 specimens. Subsequently, the behavior of steel fiber-reinforced concrete beams was investigated with and without fiber hybridization under flexural and impact loading, followed by a comparison of the results. Fiber hybridization was achieved by developing concrete containing a combination of steel and polypropylene fibers. Eighteen beam specimens of size 1650×200×150 mm were tested in the investigation. Test outcomes demonstrated that the inclusion of fibers in a hybrid form could ensure superior composite performance in terms of flexure and impact resistance when compared to the incorporation of a single type of fibers in reinforced concrete.

Keywords: Reinforced Concrete; Fiber Hybridisation; Flexure; Impact; Toughness.

1. Introduction

Concrete is the most widely used construction material due to its low cost, high strength, water resistance, ease of mouldability, and low maintenance cost. The disadvantage with conventional concrete is that it is a relatively brittle material with a low tensile strain capacity and poor fracture toughness. Concrete as a material can be reinforced with short, randomly distributed fibers to cater to its limitations related to brittleness and poor resistance to the propagation of cracks [1–5]. Steel fibers with a higher elastic modulus can also enhance the flexural toughness and ductility of concrete. The steel fibers help in bridging the propagating cracks in the concrete matrix under a higher state of stress [6]. Steel fibers used as secondary reinforcement in concrete beams can significantly improve the mechanical properties of hardened concrete [7]. Superior mechanical properties, such as higher energy absorption and improved blast resistance, make steel fiber-reinforced cementitious composites a prime choice for the development of resilient structures [8]. Numerous investigations have examined the effects of fiber dosage and type on the mechanical properties of concrete. Research indicated that the enhancements in tensile behavior provided by the corrugated steel fibers were more remarkable compared to compressive behaviors based on both fiber volume fraction and concrete matrix strength

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[9]. More recently, it was reported that hooked steel fiber-reinforced beams exhibited better torsional toughness with 1.5% fiber dosage when compared to those of beams with straight micro steel fibers [10]. However, the addition of steel fibers at high dosages to concrete is uneconomical and results in reduced workability and consistency of the mix. The addition of more than one fiber type functioning discretely can yield optimum performance by providing a balance between better fresh concrete properties and the toughness of hardened concrete [11].

Xu & Hannant (1992), Kakemi & Hannant (1995), and Mobasher & Li (1996) [12–14] have shown that deploying the idea of hybridization with two different fiber types incorporated into a common cement matrix can result in a composite that can render additional beneficial engineering properties. A well-designed hybrid composite exhibits synergy, which is a hybrid performance greater than the sum of individual fiber performances due to the positive interaction between the fibers.

Many fiber combinations may provide Synergy with hybrids based on fiber constitutive response, hybrids based on fiber dimensions, and hybrids based on fiber function as the most recognized ones [15-18]. The virtue of using a combination of organic (polypropylene and nylon) and inorganic fibers (glass, asbestos, and carbon) to derive higher tensile strength and fracture toughness by hybridization was appreciated almost 30 years ago by Walton & Majumdar [19]. Researchers have conducted several trials to recognize optimum fiber integration that can induce maximum synergy [20-24]. Hybrid fiber-reinforced concrete can be characterized as a multiphase composite of the aggregate, the interfacial transition zone, the bulk cement paste, and different fiber types. A quantitative calculation of the effect of multi-types of fiber is possible based on multi-level homogenization schemes [25]. The incorporation of non-metallic fibers as an addition to fiber-reinforced concrete can lead to better workability and reduced early age cracking. At a particular volume fraction, the non-metallic fibers have supplemented the fiber availability because of their lower-grade density compared to metallic fibers. The effectiveness of the non-metallic fibers in controlling the propagation of micro-cracks in the inelastic phase of concrete is because of their higher ductility and lower stiffness. It is necessary to employ a blend of low and high modulus fibers to curb the generation and propagation of micro and macro cracks, respectively. The hybrid combination of metallic and non-metallic fibers can render inherent benefits in improving concrete properties and the economy of concrete production [26]. Among the non-metallic fibers, the polypropylene fiber is found to have better synergistic behavior with steel fibers [27].

The action of conventional concrete under uniaxial compression can be enhanced by incorporating hybrid fibers. The hybrid response between volume fraction and aspect ratio of the metallic and non-metallic fibers is the influential factor in the improvement in uniaxial compressive strength [28]. Contributions of hybrid fiber on the cracking resistance at multiple length scales can result in the ductile failure mode of hybrid fiber-reinforced concrete material subjected to uniaxial cyclic tension. It was also found that increasing the steel fiber content had a considerable effect on enhancing the concrete cyclic tensile properties [29]. A combination of hybrid fibers and stirrups reinforcement can be provided in concrete to achieve enhanced shear behavior in reinforced concrete beams [30]. Research suggests that the post-cracking flexural resistance of hybrid fiber-reinforced concrete can be effectively increased through steel fiber addition over a 1.2% volume fraction. Durability concerns arising due to increased steel content were proved to be tackled by the addition of Silica fumes and Ground granulated blast furnace slag as mineral admixtures [31].

As found by the literature review, a combination of steel macro fibers and polypropylene fibers was represented as an optimum hybrid fiber reinforcement for concrete. Although comprehensive research in the field of hybrid fiber-reinforced concrete has been carried out over the past decades, the effect of fiber hybrid hybridization on the impact resistance of concrete is poorly addressed in the literature. There is a need to study the influence of fiber dosage of non-metallic fibers in the mechanical properties of hardened concrete subjected to impact loading. In this frame of reference, a plan of the experimental sequence was carried out to understand the mechanical properties of HFRC (Hybrid Fiber-Reinforced Concrete), containing corrugated steel macro-fibers and polypropylene fibers as the metallic and non-metallic fibers, respectively. Furthermore, the study aimed to understand the behavior of HFRC beams under impact and flexure and to compare the results with that of SFRC (Steel Fiber-Reinforced Concrete) and conventional concrete.

2. Objectives and Methodology

The following objectives were formulated for the present investigation:

- To study the fresh and hardened properties of HFRC and SFRC.
- To compare the fresh and hardened properties of HFRC with SFRC and conventional concrete.
- To compare the results of HFRC with SFRC of the same volume fraction of steel fibres.
- To study the behaviour of HFRC beams and SFRC beams under flexure and impact.
- To compare the results of HFRC beams with SFRC beams and conventional Reinforced Concrete beams under flexure and impact.

These objectives were achieved by following the methodology illustrated in Figure 1.

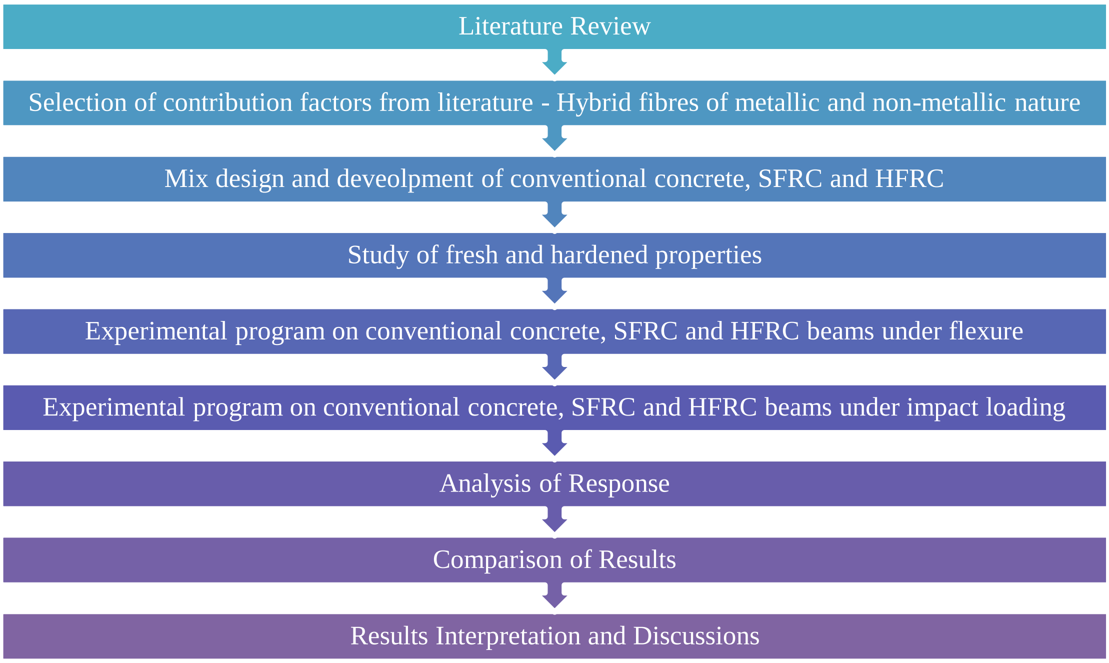


Figure 1. Flowchart of the research methodology

3. Mix Design

3.1. Materials Used

The study used ordinary Portland Cement of 53 grade confirming to IS 12269-1989 [32]. River sand with fineness modulus 2.397 and specific gravity 2.54 was used as fine aggregate. Figure 2 shows the gradation curve of fine aggregates. Crushed natural stones of sizes 20mm and 10mm were used as coarse aggregate. The 20mm-sized coarse aggregate had a specific gravity of 2.77 and fineness modulus of 7.07, while the 10mm-sized had a specific gravity of 2.75 and fineness modulus of 6.74. These aggregates were well graded in a suitable proportion as per IS 383-1970 [33], and the ratio of the 10mm to 20mm aggregate was 3:1. The coarse aggregate used in this investigation was thoroughly washed and air dried to exclude the dirt and water from its surface.

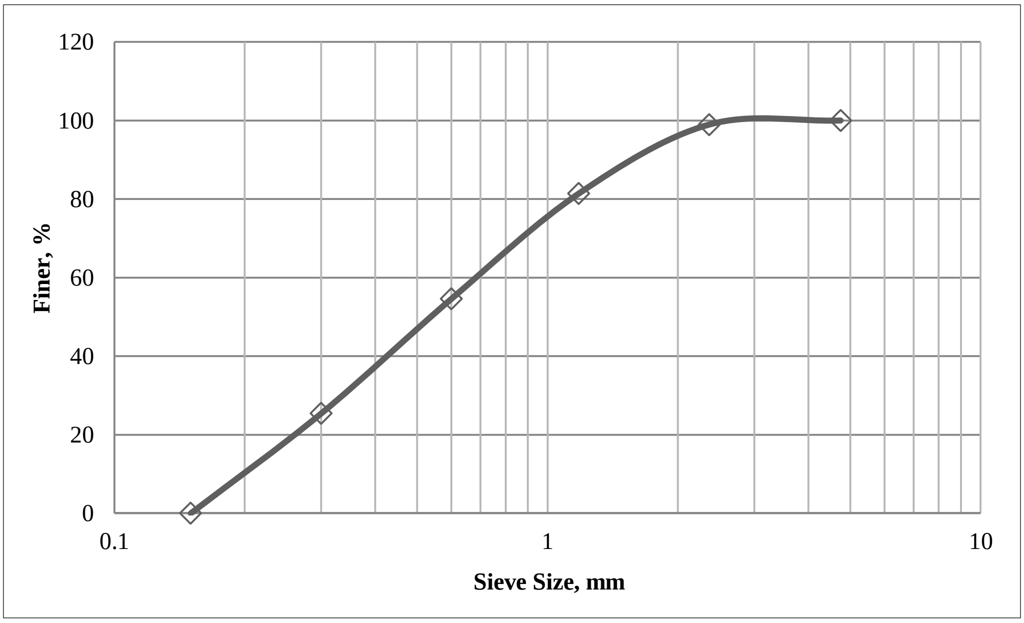


Figure 2. Particle Size Distribution of Fine Aggregate

Polypropylene fiber used in the present study was ‘Recron 3S’ of Reliance Industries Limited. Figure 3-a shows the Polypropylene fibers used in the study. The properties of the Polypropylene fibers used in the study are given in Table 1. The steel fiber used for the study was 0.45mm diameter Round Crimped and 25mm long. Figure 3-b shows the steel fiber used in the investigation. The aspect ratio of the fiber was 55 and had a density of 7.2 g/cc.

Table 1. Properties of Polypropylene Fiber

Particulars	Values
Specific gravity	$0.91 g/cm^3$
Ingredients	Virgin Polypropylene C3H6
Fiber cross-section	$18 (10^{-6})$ m
Fiber dimension	$12 (10^{-3})$ m
Modulus of Elasticity	6000-7500 MPa
Tension Capacity	350 MPa

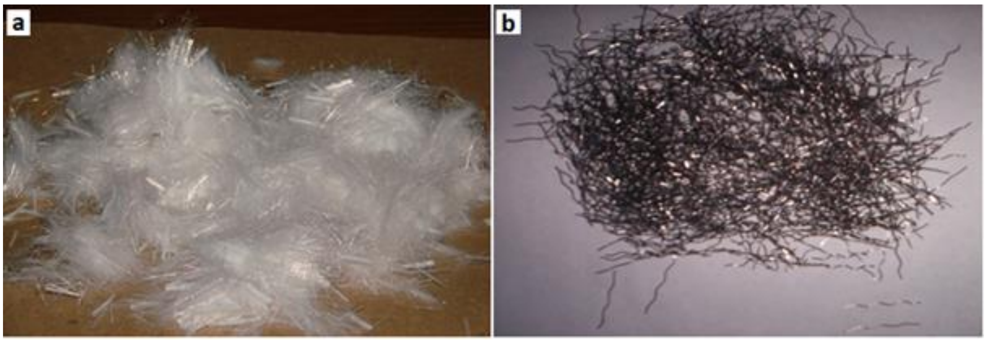


Figure 3. a) Polypropylene fibers and b) Steel fibers used in the study

3.2. Mix Proportion

A concrete mix of M25 grade was designed in a proportion of 1:1.52:3.36:0.5 by weight according to IS 10262:1982 [34]. Control samples with no fiber content, steel fiber-reinforced concrete (SFRC) containing only steel fibers, and hybrid fiber-reinforced concrete (HFRC) containing steel and polypropylene fibers were prepared from the same mix. The SFRC mixes were developed by varying dosages of steel fiber to get an optimum level of fiber combination. The steel fiber dosage ranged from 0% to 2% with increments of 0.5% of the volume fraction of concrete. HFRC mixes were also developed by different dosages of steel fiber to get an optimum level of fiber combination. The steel fiber dosage ranged from 0% to 2% with increments of 0.5% of the volume fraction of concrete, and the polypropylene fiber was at a fixed quantity of 0.2% of the weight of cement for all the combinations. Thus, a total of nine mixes were developed. Table 2 shows the designations for the different mixes with varying fiber content.

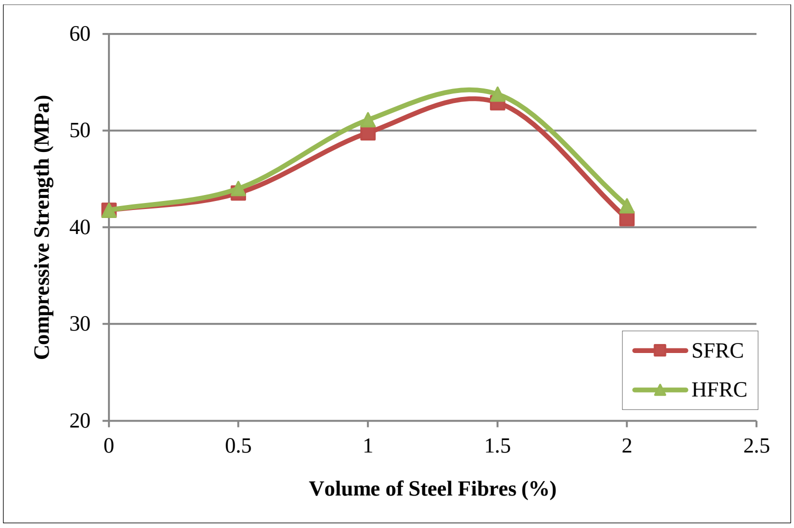
Table 2. Mix Designation with Varying Fiber Content

Type of Mix	Steel Fiber % (volume of concrete)	Polypropylene Fiber % (weight of cement)	Mix Designation
Control	0	0	SF0
SFRC	0.5	0	SF5
	1.0	0	SF10
	1.5	0	SF15
	2.0	0	SF20
HFRC	0.5	0.2	SF5P
	1.0	0.2	SF10P
	1.5	0.2	SF15P
	2.0	0.2	SF20P

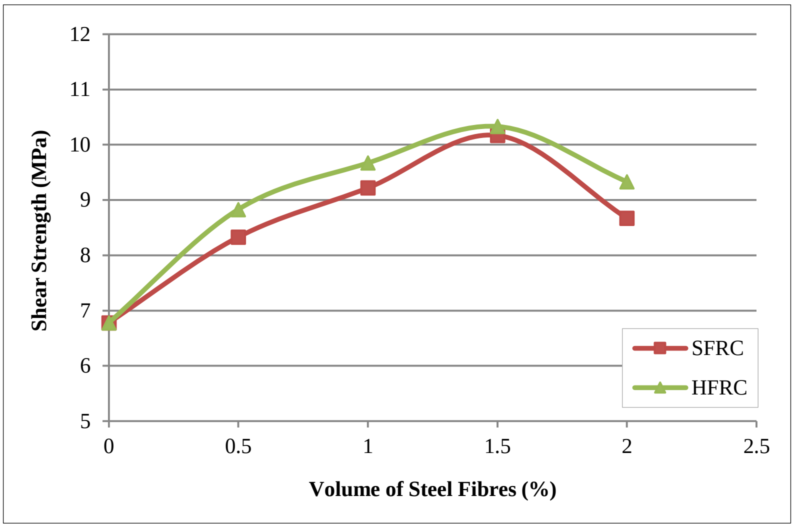
3.3. Hardened Properties

A total of 135 specimens were cast, which included 54 cubes (150mm) for testing the compressive and shear strength, 54 cylinders (150mm dia×300mm long) for compressive strength test, split tensile strength test, and modulus of elasticity, and 27 prism specimens (10×10×50cm) for testing the strength under flexural loading. These specimens were tested for different mechanical properties. Figure 4 shows the variation of compressive strength, shear strength, flexural strength, split tensile strength, and the modulus of elasticity with various percentages of fiber content, respectively.

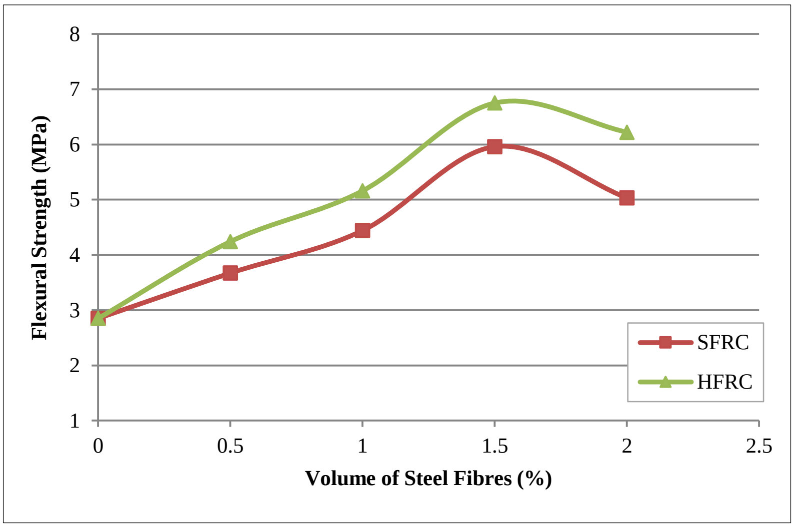
There was no reduction in strength due to the addition of fibers. The performance of HFRC was superior to SFRC in terms of compressive strength. The addition of hybrid fibers caused an increase in the strength values compared to that of SFRC. However, the addition of steel fibers >1.5% volume fraction adversely affected the hardened properties of SFRC and HFRC. When the quantity of fiber in the particular mix increases, the workability is affected as the filling ability reduces, which, in turn, affects the compaction. The pull-out resistance of the fibers would be lesser at this stage, and hence reduction in the strength of concrete was observed for mixes with >1.5% volume fraction. The addition of a 1.5% percentage of steel fiber volume contributed to the betterment of hardened properties of concrete for HFRC and SFRC for all the mixes of concrete examined in this study. Thus, the optimum steel fiber content for improved behavior of SFRC and HFRC was between 1% and 1.5% in the current study.



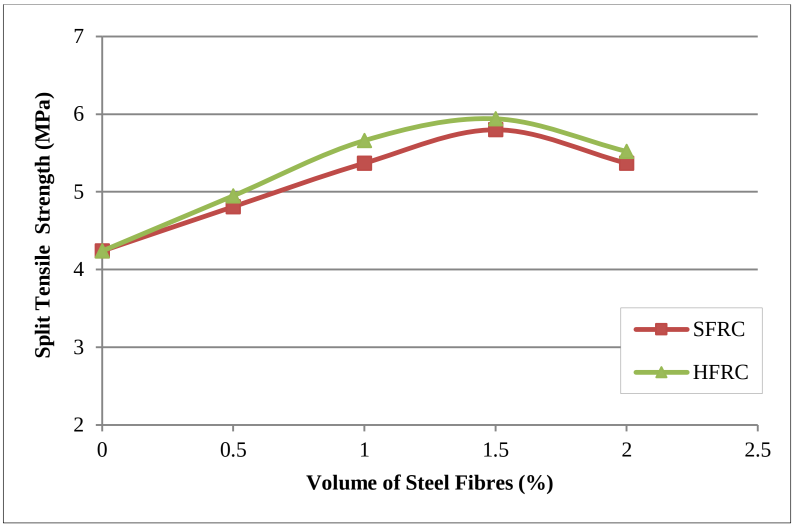
(a) Variation of compressive strength with steel fiber volume



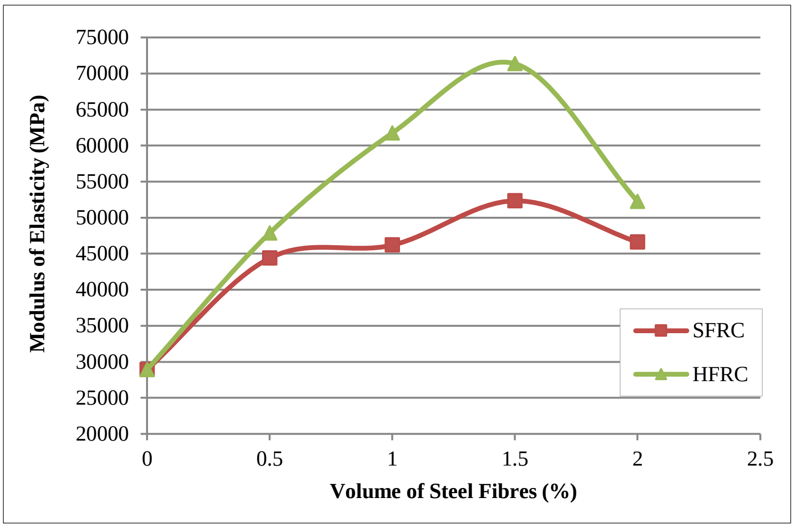
(b) Variation of shear strength with steel fiber volume



(c) Variation of flexural strength with steel fiber volume



(d) Variation of split tensile strength with steel fiber volume



(e) Variation of modulus of elasticity with steel fiber volume

Figure 4. Comparison of hardened properties of SFRC and HFRC

4. Experimental Plan

4.1. Details of Test Specimens

The beams used as the test specimens were designed as under reinforced sections as per IS 456:2000 [35] stipulations. All the beams had the same dimensions, with an overall length of 1.65m and an effective span of 1.5m. The cross-sectional area of the beam was 150×200mm with an effective depth of 162mm. The clear cover provided was 25mm. Figure 5 shows the details of the reinforcement provided in the test specimens.

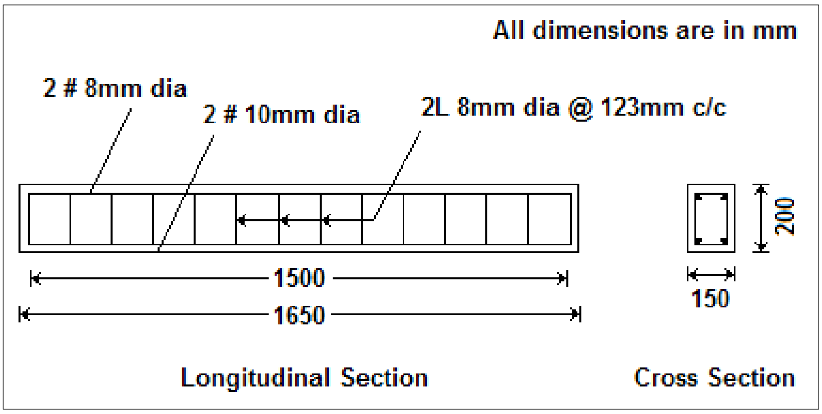


Figure 5. Reinforcement details of test specimen

4.2. Preparation of Test Specimens

The present study used beams of size 1650×200×150mm. The tests were conducted on HFRC, SFRC, and conventional concrete beams separately under flexure and impact loading. Conventional concrete beams had no fiber content. Four types of SFRC beams were provided by varying the steel fiber dosages to get an optimum level of fiber combination. The steel fiber dosage ranged from 0 to 2%, with increments of 0.5% of the volume fraction of concrete. Four types of HFRC beams were provided by varying the steel fiber dosages to get an optimum level of fiber combination. The steel fiber dosage was at a range of 0 to 2% with increments of 0.5% of the volume fraction of concrete, and the polypropylene fiber was at a fixed quantity of 0.2% of the weight of cement for all the combinations.

The concrete was mixed in a laboratory-type pan mixer. A high-range water-reducing naphthalene-based superplasticizer was employed to enhance the workability of fresh concrete. HYSD bars with diameters of 10mm and 8mm contributed as the main reinforcement and stirrup holders, respectively. Table 3 presents the properties of the reinforcement bars. A total of nine beams were cast for experiments under flexure, and another nine beams were cast for tests under impact loading. Thus, a total of 18 beam specimens of size 1650×200×150mm were cast and tested in this investigation. Table 4 shows the details of various beams. Figure 6-a represents the details of the casting of the beam specimens. The beams were water cured by covering them with wet gunny bags for the next 27 days as shown in Figure 6-b.

Table 3. Properties of Reinforcement Bars

Property	10mm diameter bar	8mm diameter bar
Young's Modulus (GPa)	247.48	225.42
Yield stress (MPa)	455.45	434.54
Ultimate stress (MPa)	524.35	501.24

Table 4. Details of Beam Specimens

Type of Beam	Steel Fiber (% volume of concrete)	Polypropylene Fiber (% weight of cement)	Mix Designation	Compressive Strength of concrete (28 days)	Beam Designation
Control Beam	0	0	SF0	41.7	CB-S0
SFRC beams	0.5	0	SF5	43.5	B-S5
	1.0	0	SF10	49.7	B-S10
	1.5	0	SF15	52.8	B-S15
	2.0	0	SF20	40.8	B-S20
HFRC beams	0.5	0.2	SF5P	44.0	B-S5P
	1.0	0.2	SF10P	51.1	B-S10P
	1.5	0.2	SF15P	53.7	B-S15P
	2.0	0.2	SF20P	42.2	B-S20P

Figure 6. Development of test specimens: a) Casting of the specimens b) Curing of the specimens

5. Flexure Testing Program

Flexure test was performed on the test specimens under two-point loading with a total span of 1.5m and pure bending at central zone of 500 mm. The schematic diagram of the flexure test setup is shown in Figure 7-a. A proving ring of capacity 500 kN was used to measure the applied load. Load was applied with an increment of three divisions of proving ring. A square rod was used as the spreader beam. Three dial gauges of accuracy 0.01mm were used to measure the deflection at mid span and at the load points. The load at which first crack occurred was noted and the propagation of cracks were marked on the surfaces for every interval of loading. The crack width for every increment of loads until failure was noted using a micrometer microscope of accuracy 0.1mm. The ultimate load was also noted. The details of the test setup for flexural loading are shown in Figure 7-b.

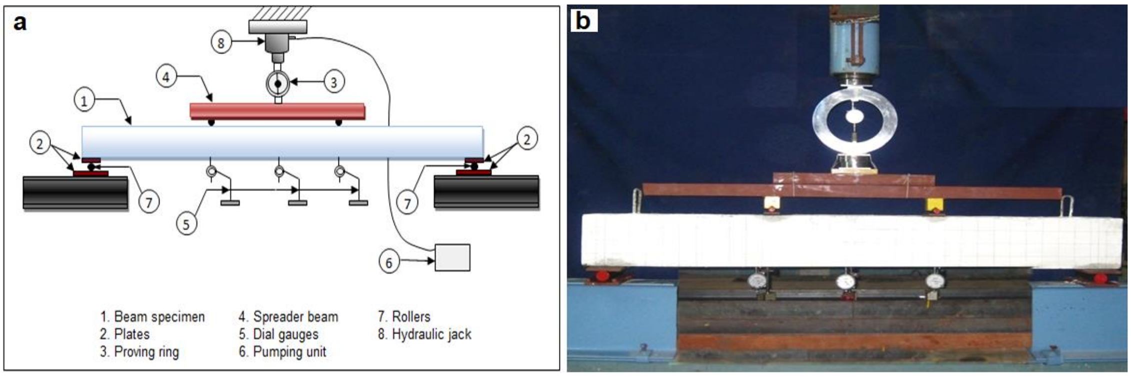
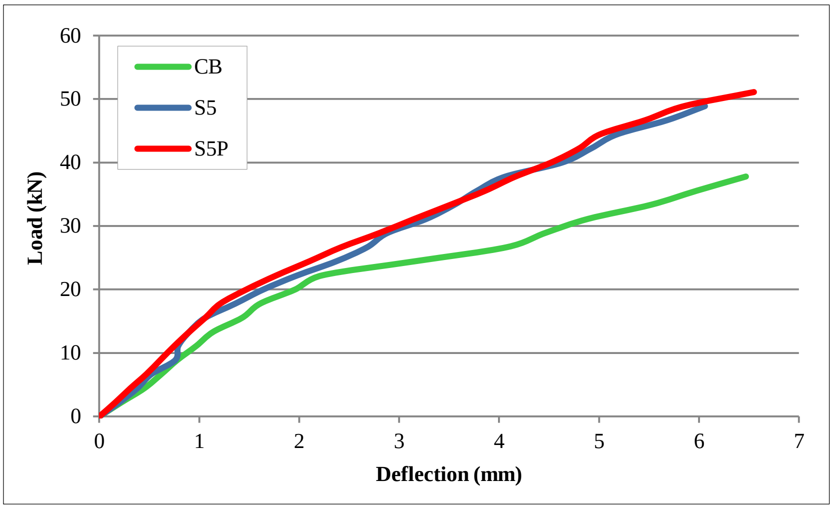


Figure 7. Flexure test: a) Schematic Diagram b) Test Setup for Flexural Loading

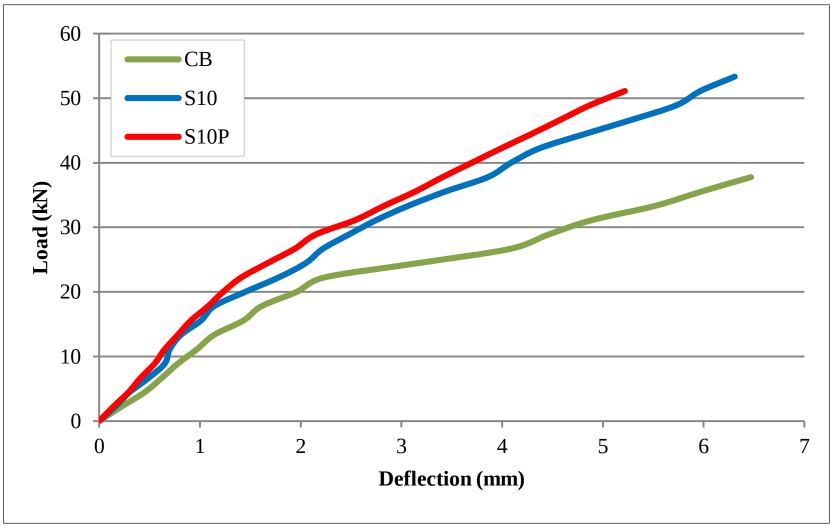
The behaviour of ordinary concrete beams, SFRC beams and HFRC beams were studied under static flexural loading. The specimens were evaluated for deflection, crack pattern, crack-width, first cracking load and ultimate load carrying capacity under flexural loading.

5.1. Load-Deflection Characteristics

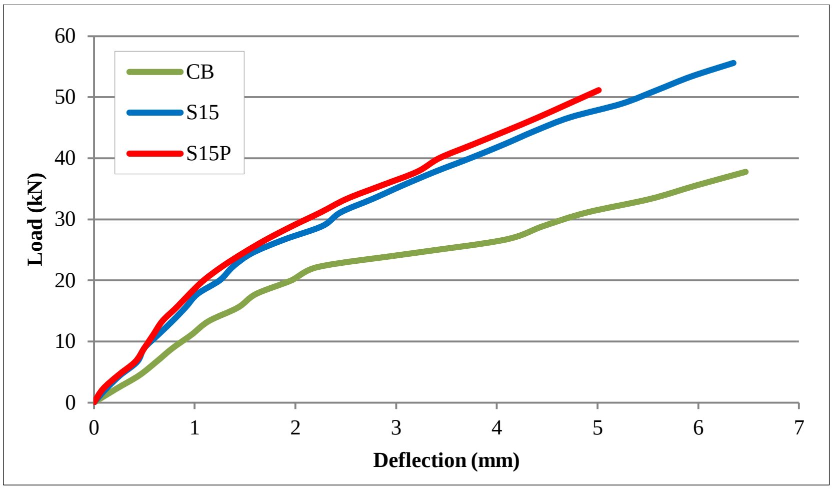
Comparison of deflection of the HFRC with SFRC beams of same steel fiber volume up to 5mm is shown in Figure 8. The deflection is observed to be increased for all the test specimens post the first crack load as identified in the bilinear deflection curves. The curves indicate higher flexural toughness for the fiber reinforced beams compared to the plain concrete without fibers. It was also observed that the hybrid fiber reinforced concrete beams, for a low dosage of steel fibers (1-1.5%) was tougher than the steel fiber reinforced beams indicating a possible synergy in the action of steel-polypropylene fibers.



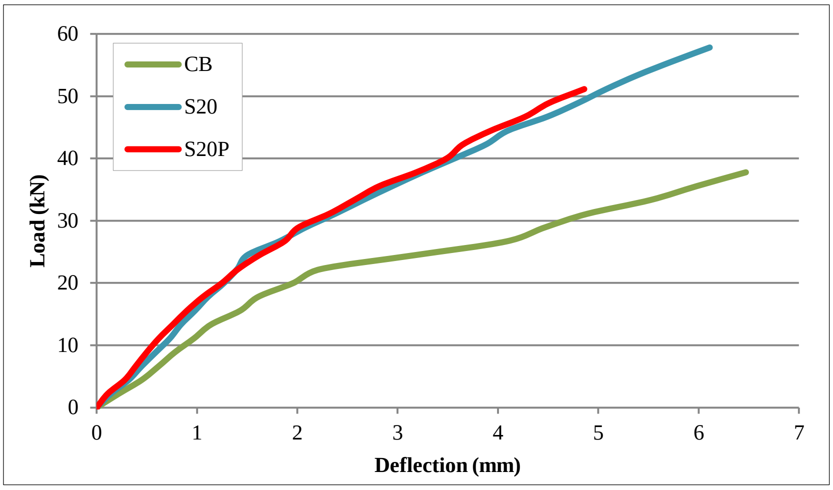
(a) Deflection of Beam Specimens- CB, BS5, BS5P



(b) Deflection of Beam Specimens- CB, BS10, BS10P



(c) Deflection of Beam Specimens- CB, BS15, BS15P



(d) Deflection of Beam Specimens- CB, BS20, BS20P

Figure 8. Comparison of deflection of the HFRC with SFRC beams

5.2. First Crack Load and Ultimate Load

The initiation of first crack was carefully observed and the corresponding loading was noted down. Table 5 shows the load at which the first crack was captured in the test specimens. The ultimate load carrying capacity of the specimens is also shown in the same table. A standardization factor S_f in Equation 1 was multiplied with the first crack load and ultimate load to calculate the standardized first crack and ultimate load values.

$$S_f = \sqrt{\frac{f_{ca(ave)}}{f_{ca}}} \tag{1}$$

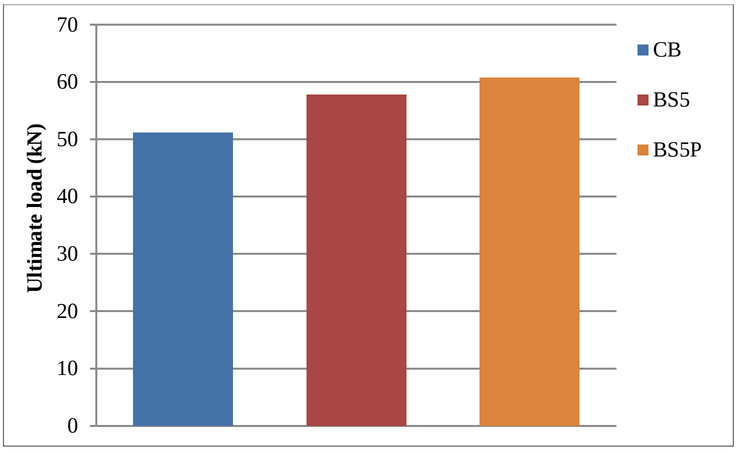
where f_{ca} is the average compressive strength of a typical specimen, $f_{ca(ave)}$ is the average compressive strength of all the test specimens [36]. From the results it was observed that the test specimens with fibers have demonstrated improved load carrying capacity at initiation of first crack and at failure.

Table 5. Load Carrying Capacity of Test Specimens

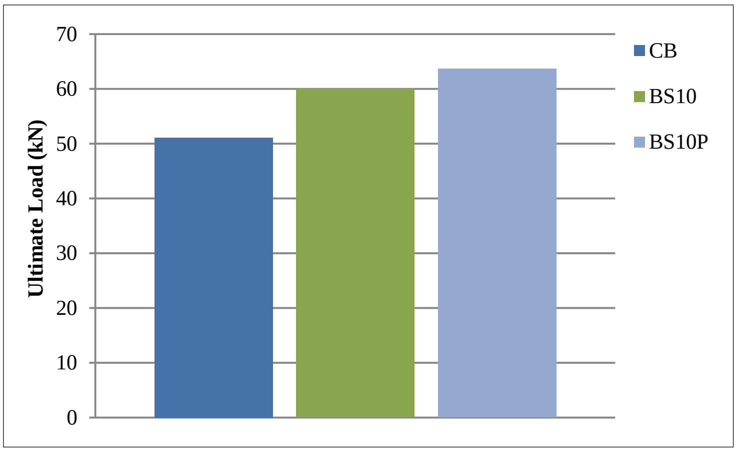
Beam Designation	Load at first crack		Ultimate Load		$P_{cra.sta}$ (kN)	$P_{u.sta}$ (kN)	P_u/P_{cra}
	P_{cra} (kN)	Ratio of increase	P_u (kN)	Ratio of increase			
CB-S0	20.01	-	51.13	-	21.15	54.04	2.56
B-S5	22.23	1.11	57.80	1.13	23.01	59.82	2.60
B-S10	24.45	1.22	60.02	1.17	23.67	58.10	2.45
B-S15	28.90	1.44	66.69	1.30	27.14	62.62	2.31
B-S20	26.68	1.33	62.99	1.23	28.49	67.27	2.36
B-S5P	24.45	1.22	60.76	1.19	25.18	62.58	2.49
B-S10P	26.68	1.33	63.73	1.25	25.51	60.93	2.39
B-S15P	31.12	1.55	67.43	1.32	29.00	62.84	2.17
B-S20P	28.90	1.44	64.47	1.26	30.37	67.76	2.23

The increase in first crack load for SFRC beams varies from 1.11 times to 1.44 times than that of ordinary concrete beams, whereas the increase in first crack load for HFRC beams varies from 1.22 times to 1.55 times than that of the control beams. Thus, the addition of hybrid fibers caused an increase of 11% in the first crack load of the beams when compared to the ordinary concrete beams. The increase in ultimate load for SFRC beams varies from 1.13 times to 1.3 times than that of ordinary concrete beams, whereas the increase in ultimate load for HFRC beams varies from 1.19 times to 1.32 times than that of ordinary concrete beams. Thus, the addition of hybrid fibers caused a marginal increase of 2% in the ultimate load of the beams when compared to the ordinary concrete beams.

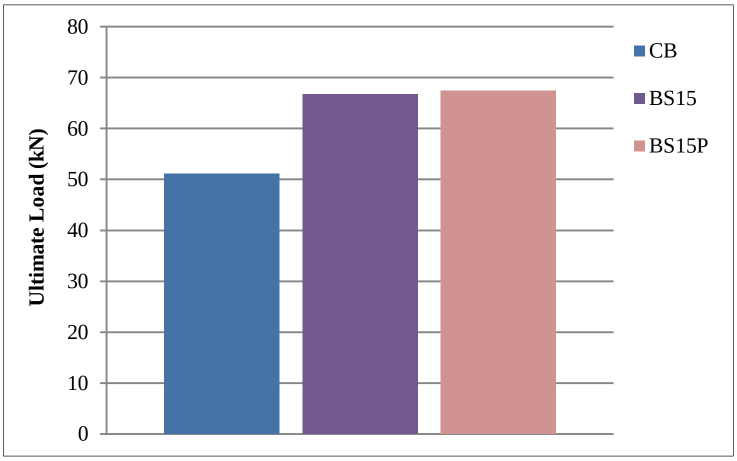
Comparison of ultimate load of the HFRC with SFRC beams of same steel fiber volume is shown in Figure 9. From the graphs, it was observed that the ultimate load of both the SFRC beams and HFRC beams increased with the increase in steel fiber volume up to 1.5%. Addition of steel fibers above 1.5% volume fraction reduced the ultimate load carrying capacity of both SFRC beams and HFRC beams. This is because of formation of voids and honeycombing due to less workability and improper compaction. Hence, the optimum steel fiber content for improved behaviour of SFRC beams and HFRC beams under flexure is between 1% and 1.5% in this study. From the graphs, it was also observed that the ultimate load of the HFRC beams is greater than that of the SFRC beams for all the steel fiber volume fractions.



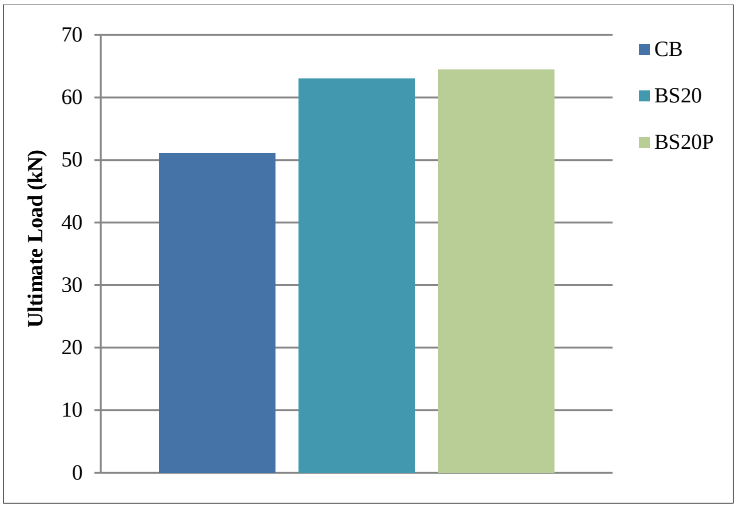
(a) Variation of ultimate load for Beam Specimens- CB, BS5, BS5P



(b) Variation of ultimate load for Beam Specimens- CB, BS10, BS10P



(c) Variation of ultimate load for Beam Specimens- CB, BS15, BS15P



(d) Variation of ultimate load for Beam Specimens- CB, BS20, BS20P

Figure 9. Comparison of ultimate load of the HFRC with SFRC beams

5.3. Crack-width

The crack-width for all the beam specimens was observed using a micrometre of accuracy 0.1mm. The crack-width was measured right from the initiation of first crack till the ultimate load. Table 6 shows the maximum number of cracks and maximum crack width at the ultimate load. Addition of hybrid fibers has caused to increase the total number of cracks developed in the beam when compared to the control beam, but of reduced width. Maximum crack width measured in HFRC beams was lesser than that of SFRC beams under flexure. From the study it was also noticed that at the ultimate load, the crack width in fiber reinforced beams was lesser than that of conventional concrete because of the fiber-matrix bonding. As per IS 456: 2000 [35], clause 35.3.2 (pertaining to limits of serviceability), the surface width of the cracks should not exceed 0.3mm for mild exposure conditions. Table 6 also presents the load which produced 0.3mm crack width for the different series of beams. A crack width of 0.3mm was measured in all the tested beams after the beams were loaded beyond the service moment. This clearly indicates that the HFRC beams were safe in mild exposure condition.

Table 6. Maximum Crack Width and number of cracks at Ultimate Load

Beam Designation	Ultimate load P_u (kN)	Load at 0.3mm Crack width $P_{cra,0.3}$ (kN)	Maximum crack width (mm)	Maximum number of cracks
CB-S0	51.13	35.57	3.5	10
B-S5	57.80	46.68	3.1	13
B-S10	60.02	48.91	3	13
B-S15	66.69	53.35	2.7	16
B-S20	62.99	57.80	2.5	11
B-S5P	60.76	53.35	2.8	14
B-S10P	63.73	54.83	2.7	14
B-S15P	67.43	58.54	2.3	17
B-S20P	64.47	60.02	2.1	15

5.4. Failure Mode

The cracks developed on the test specimens were closely observed and pointed while loading progressed during the test. The crack patterns of the various test specimens are shown in Figure 10. From the pattern, it was observed that both SFRC beams and HFRC beams had developed a greater number of cracks when compared to the ordinary beams, but of reduced crack width. The rate of crack propagation in both the types of fiber reinforced beams was observed to be lesser than that in the control beam indicating strong fiber-matrix bonding in the fiber reinforced concrete beams.

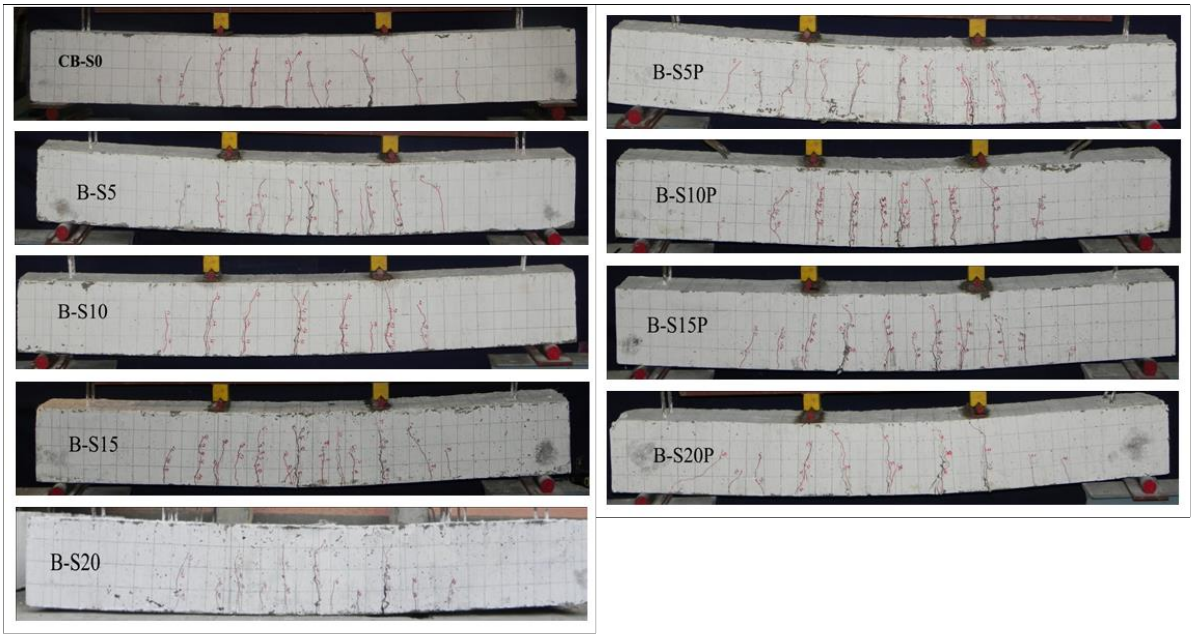


Figure 10. Crack Pattern of Test Specimens under Flexure

6. Impact Testing Program

Impact test on beams was performed by drop test. Dropping a weight of steel ball with a mass of 21kg stimulated the impact loading. The diameter of the steel ball was 180 mm. Two concrete pedestals with a mass of 500kg with end fixtures were utilized to anchor the beam firmly to its position during impact. Beams were supported by rollers held in position using plates bolted to the pedestals. Figure 11-a shows the schematic diagram for the impact test. The weight decreased at mid-span from a height of 0.5m above the top surface of the beam. The total energy absorption, crack pattern, and crack-width were the parameters selected for the study. The number of blows required to form the first crack was considered for each beam while also considering the total number of cracks formed in each specimen. Loading continued until spalling of the compression zone occurred. Figure 11-b indicates the details of the impact test setup.

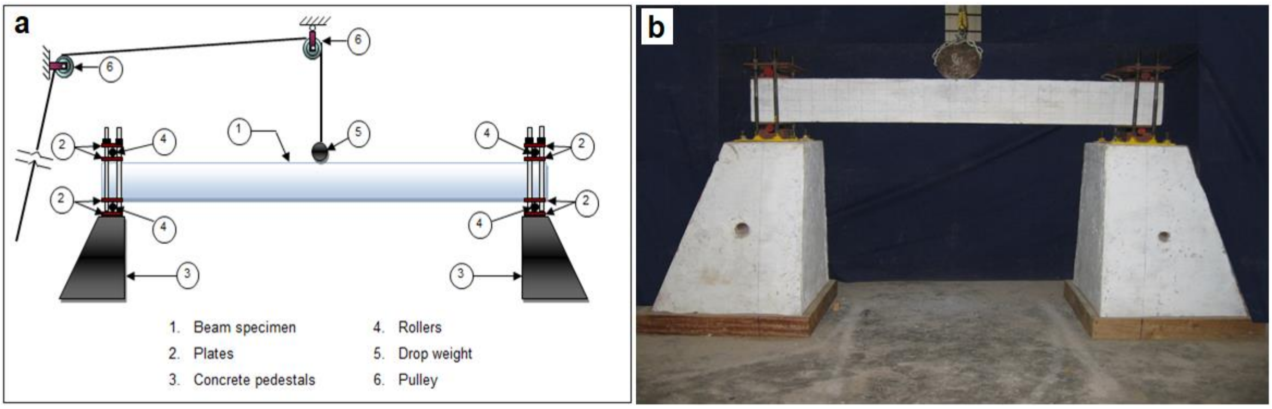


Figure 11. Impact test: a) Schematic Diagram b) Test Setup for Impact Loading

As observed, all the specimens subjected to impact loading failed by spalling of concrete at the vicinity of the point of impact. The aspects evaluated under impact loading were energy absorbed till the first crack, energy absorbed till spalling occurred, crack pattern, and crack width at an ultimate load of the test specimens. The strength of the concrete under impact loading was evaluated based on the number of blows till failure. The toughness of concrete, as a measure of the energy absorption capacity, was directly evaluated from the number of blows and drop heights.

6.1. First Crack and Spalling

There were observations of the number of blows from a drop height of 0.5m, which was adequate to develop the first crack, and the total number of blows leading to failure in each specimen. Table 7 presents the acquired data for each specimen.

Table 7. Total Count of Blows for First Crack and Spalling

Beam Designation	Number of blows for initiation of first crack	Number of blows for spalling
CB-S0	1	48
B-S5	1	102
B-S10	2	126
B-S15	2	130
B-S20	2	110
B-S5P	1	118
B-S10P	2	132
B-S15P	3	145
B-S20P	2	128

6.2. Energy Absorption

From the number of blows and drop heights, energy absorbed for the initiation of the first crack and failure was determined. The energy absorbed by each specimen is calculated by Equation 2.

$$E = mg(h_1 + h_2 + h_3 ... + h_n) \tag{2}$$

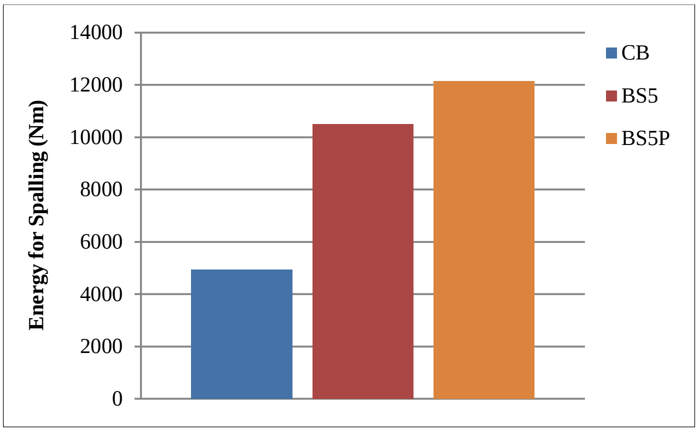
where E is energy absorbed, m is mass of the drop weight (Steel ball-21kg), g is acceleration due to gravity (9.81m/s^2), h is drop height in m, n is total number of blows. The total energy for the initiation of the first crack and spalling is shown in Table 8. The standardized values of total energy for spalling were calculated as well.

Table 8. Total Energy for First Crack and Spalling

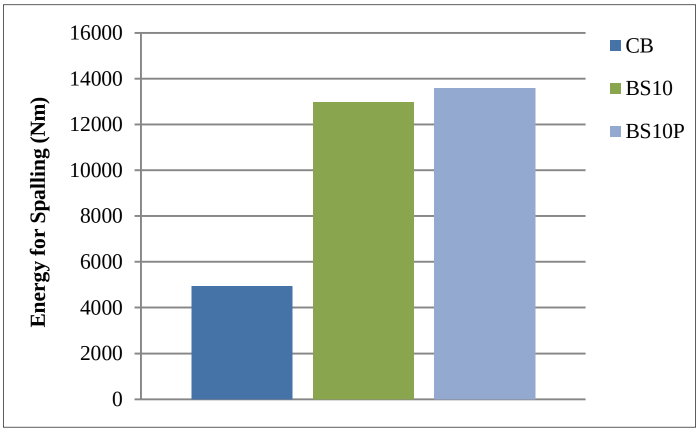
Beam Designation	Total energy required for initiation of first crack (N-m)	Total energy required for spalling		Standardized Total energy required for spalling (N-m)
		(N-m)	Ratio of increase	
CB-S0	103.005	4944.24	-	5226.06
B-S5	103.005	10506.51	2.13	10874.24
B-S10	206.01	12978.63	2.63	12563.31
B-S15	206.01	13390.65	2.71	12573.82
B-S20	206.01	11330.55	2.29	12101.03
B-S5P	103.005	12154.59	2.46	12519.23
B-S10P	206.01	13596.66	2.75	12998.41
B-S15P	309.015	14935.73	3.02	13920.10
B-S20P	206.01	13184.64	2.67	13857.06

There were no significant outcomes on the total energy absorbed till the development of the first crack as a result of fiber addition. However, fracture energy of fiber-reinforced test specimens was greater than those of conventional concrete test specimens. The increase in energy absorption for SFRC beams varied from 2.13 to 2.71 times that of ordinary concrete beams, whereas the increase in energy absorption for HFRC beams was at a range of 2.46 to 3.02 times that of the conventional concrete beams. The addition of hybrid fibers caused an increase of 31% in the toughness of the beams than that of SFRC beams under impact.

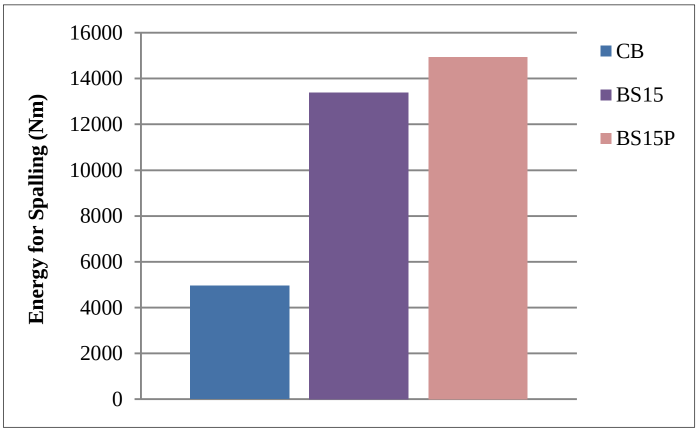
Figure 12 shows a comparison of the plot of energy absorption capacity exhibited by the HFRC and SFRC beams of the same steel fiber volume. According to the graphs, the energy absorption of both the SFRC beams and HFRC beams increased with the increase in steel fiber volume up to 1.5%. The addition of steel fibers above 1.5% volume fraction reduced the energy absorption capacity of both SFRC and HFRC beams. This is because of the formation of voids and honeycombing due to poor workability and lack of compaction. Thus, the optimum steel fiber content for improved behavior of SFRC beams and HFRC beams under impact was between 1% and 1.5% in this study. Based on the graphs, the energy absorption capacity of the HFRC beams was greater than that of the SFRC beams for all the steel fiber volume fractions.



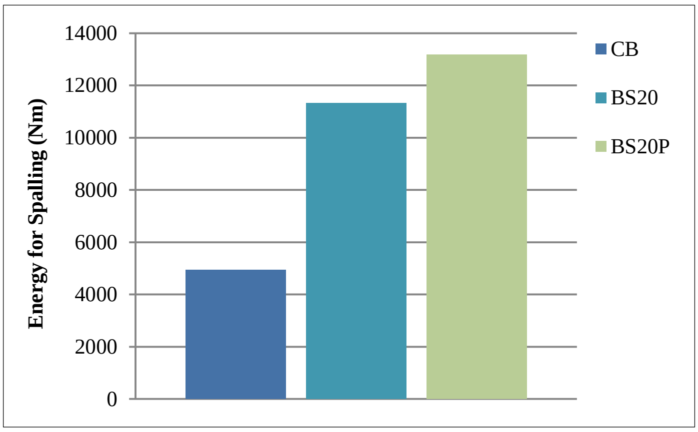
(a) Variation of energy absorption for Beam Specimens- CB, BS5, BS5P



(b) Variation of energy absorption for Beam Specimens- CB, BS10, BS10P



(c) Variation of energy absorption for Beam Specimens- CB, BS15, BS15P



(d) Variation of energy absorption for Beam Specimens- CB, BS20, BS20P

Figure 12. Comparison of the plot of energy absorption capacity exhibited by the HFRC and SFRC beams

6.3. Crack-width

The crack width for all the beam specimens was observed using a micrometer with an accuracy of 0.1mm. As noted, the maximum crack width measured in the fiber-reinforced beams was less than that of ordinary concrete beams when exposed to impact loading. This shows that the steel and polypropylene fibers in the matrix resisted the propagation of cracks. Table 9 presents the total number of cracks formed and the maximum crack width observed in each beam series.

Table 9. Total number of Cracks and Maximum Crack Width

Beam Designation	Number of Cracks	Maximum Crack width (mm)
CB-S0	11	3.3
B-S5	10	3.1
B-S10	12	2.9
B-S15	10	2.7
B-S20	8	2.7
B-S5P	10	2.8
B-S10P	10	2.7
B-S15P	12	2.6
B-S20P	14	2.3

6.4. Failure Mode

Figure 13 shows the crack pattern of various beams under the impact load. According to the pattern, the crack width for the hybrid fiber-reinforced beams was less than that of the conventional concrete test specimens when exposed to impact loading. Hence, the synergic combination of polypropylene and steel fibers in the matrix offers resistance to the propagation of the internal micro-cracks.

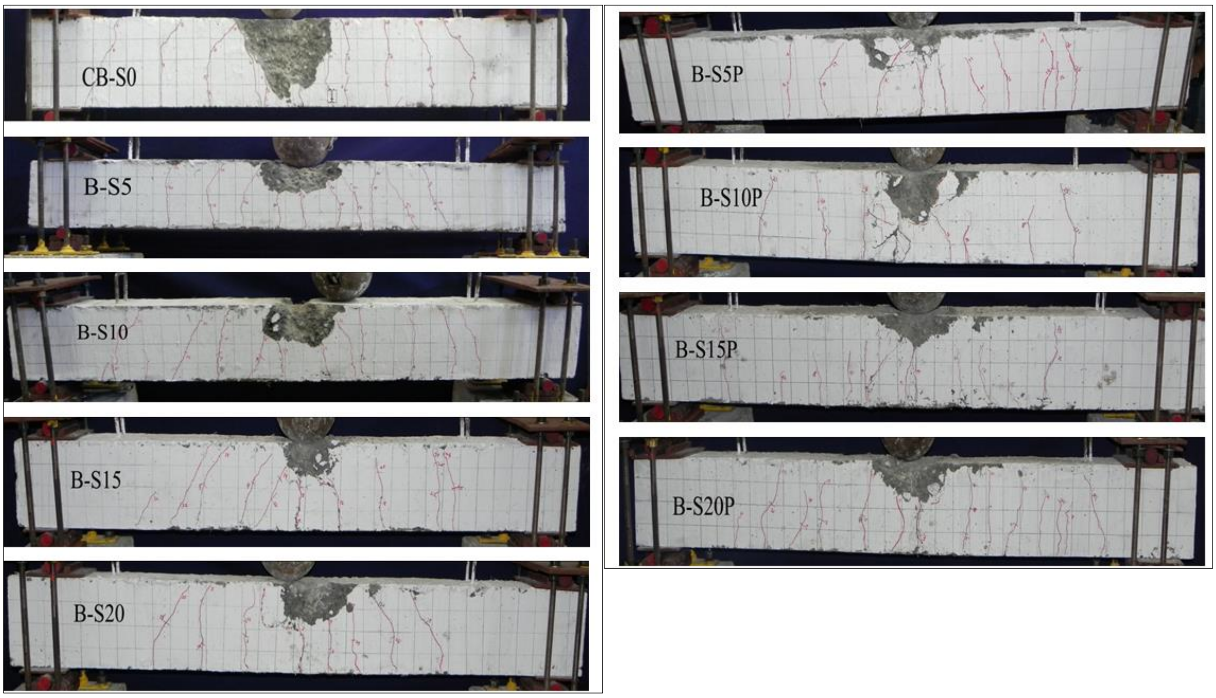


Figure 13. Crack Pattern of Test Specimens under Impact

7. Discussion

Steel fiber content ranging from 0 to 2% with increments of 0.5% by volume of concrete content were added to obtain SFRC mixes. To obtain HFRC mixes, steel fiber dosage varied from 0 to 2% with increments of 0.5% of the volume fraction of concrete while maintaining the polypropylene fiber at a fixed dosage of 0.2% of the weight of cement. Thus, a total of nine mixes were developed, including the control mix without fibers. The properties of fresh HFRC were studied and compared with ordinary concrete and SFRC. A total number of 135 standard specimens were tested to study the properties of hardened HFRC viz., compressive strength, flexural strength, splitting tensile strength, modulus of elasticity, and shear strength. Critical analysis of the results showed that fiber could yield a better performing concrete if added with proper care to maintain workability. The optimum steel fiber content was between 1% and 1.5% to improve the behavior of SFRC and HFRC mixes considered in the study.

Analysis of the results obtained from the experiments under both impact and static loading indicated that the fiber-reinforced beams had better performance than the ordinary beams. The behavior of the HFRC beams under impact was superior to that of the SFRC beams for all the steel fiber volume fractions. Thus, concrete with enhanced toughness can be developed by hybridizing fiber reinforced concrete. The addition of non-metallic fibers in this study at a low volume fraction manifested a 31% increase in toughness of fibrous concrete when compared to that of nonhybridized fiber-reinforced concrete. The non-metallic fibers, with less density, will be liberally available in the concrete matrix to bridge a large number of microcracks in the interfacial transition zone. The pull-out resistance of numerous polypropylene fibers in the matrix enhances the progressive redistribution of stress across the matrix, with controlled cracking eventually increasing the strength and toughness of concrete. Better crack control due to the synergy of metallic and non-metallic fibers viz., steel and polypropylene fibers used in this study, is inferred as the reason for the enhanced strength and toughness.

8. Conclusions

According to the experimental results, it is evident that it is possible to develop concrete with enhanced strength and improved toughness using hybrid fibers at low fiber volume fractions. Increased polypropylene fiber availability in the hybrid fiber system due to its lower density and the ability of polypropylene fibers to bridge micro-cracks leads to an amplification in strength and toughness properties. The following conclusions are out from the present study:

- Under flexural loading, the addition of hybrid fibers has resulted in a maximum increase of 1.32 times the ultimate load-carrying capacity compared to conventional concrete beams.
- The addition of hybrid fibers caused a marginal increase of 2% in the ultimate load and an increase of 11% in the first crack load compared to that of SFRC beams under flexure.
- The addition of steel and polypropylene fibers increased the total number of cracks developed compared to the case of ordinary beams under flexure but of reduced width. The maximum crack width measured in the fiber-reinforced concrete test specimens under flexural loading was less when compared to that of conventional concrete ones. Additionally, the crack width measured in HFRC beams was less than that of SFRC beams under flexure.
- The addition of fiber did not manifest any remarkable outcome in the total energy absorption of the test specimens subjected to impact loading till the initiation of the first crack.
- The maximum increase in impact toughness for the SFRC and HFRC beams was 2.71 and 3.02 times greater than that of ordinary beams, respectively.
- The addition of hybrid fibers caused an increase of 31% in the energy absorption (impact toughness) when compared to that of the SFRC beams under impact.
- Fiber-reinforced beams subjected to impact developed cracks with less width when compared to ordinary concrete beams. The maximum crack width in HFRC beams was less than that of SFRC beams under impact.

This study will enhance the use of HFRC in practical situations by helping practitioners arrive at the appropriate fiber dosage based on the area of application. This study can also encourage researchers to conduct more parametric investigations in this area, which will help to develop standards to use various fibers with better engineering properties.

9. Declarations

9.1. Author Contributions

Conceptualization, M.M.M.S. and S.R.S.; methodology, M.M.M.S. and S.R.S.; resources, M.M.M.S. and S.R.S.; experimental program, M.M.M.S.; data curation, M.M.M.S. and S.R.S.; writing—original draft preparation, M.M.M.S. and S.R.S.; writing—review and editing, M.M.M.S. and S.R.S. All authors have read and agreed to the submitted version of the manuscript.

9.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

9.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

9.4. Conflicts of Interest

The authors declare no conflict of interest.

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