INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 16-12-2024

Accepted: 06-02-2025

Published: 25-02-2025

Citation: Manoj D, Purusothaman M (2025) Mechanical Properties and Flexural Behaviour of Basalt and Polypropylene Fiber Reinforced Concrete Beams. Indian Journal of Science and Technology 18(7): 517-525. https://doi.org/10.17485/IJST/v18i7.4033

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Mechanical Properties and Flexural Behaviour of Basalt and Polypropylene Fiber Reinforced Concrete Beams

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Abstract

Objectives: The intent of the study is to assess the strength and flexural behavior of hybrid fiber reinforced concrete beams containing both basalt fiber and polypropylene fibers. **Methods:** Basalt fibers were added in volume fractions of 0%, 0.25%, 0.5%, 0.75%, and 1% into the Polypropylene fiber reinforced concrete mixture. The mechanical properties of concrete, such as compressive strength, flexural strength, and modulus of elasticity, were obtained for conventional concrete, polypropylene fiber reinforced concrete, and hybrid fiber reinforced concrete mixes through standard testing procedures. The right equipment has been used to do the measurements related to the aforementioned parameters. **Findings:** The introduction of basalt fibers and polypropylene fibers caused a significant effect on the compressive strength and flexural behavior of concrete beams. The results indicated that the inclusion of basalt and polypropylene fibers exhibited a maximum increase of 18.60% and 9.70% compared to the conventional and PP FRC respectively, a maximum increase of 32.29% and 26.11% in flexural strength compared to the conventional and PP FRC respectively. **Novelty:** The article reveals that inclusion of basalt and polypropylene fibre reinforced concrete in public spaces is a promising practice, since they are impacted by adverse environmental conditions, suffer surface degradation, and are the target of vandalism. It is clear that using concrete with improved characteristics will be advantageous.

Keywords: Basalt Fiber; Polypropylene Fiber; Flexural Strength; Fiber Reinforced Concrete; Deflection

1 Introduction

Concrete's excellent plasticity, strong steel bond, affordability, durability, and compressive strength make it a preferred architectural material for infrastructure building. However, its usefulness is limited by poor tensile strength, low toughness, and fracture susceptibility[1]. To improve the ductility of concrete, it is reinforced with fiber-reinforced polymer (FRP). Researchers have carried out a number of trials with FRP bars; it improved its compressive strain properties and postponed crushing as well as boost load carrying ability. It is found that adding randomly distributed microfibers to the concrete mix increases the ductility and deformability of FRP-reinforced concrete [2]. Metallic, polymeric, mineral, and naturally occurring fibers were among the types of fibers used to make concrete; steel fibers outperformed the others due to their high modulus of elasticity and tensile strength, and steel-fiber concrete has been used extensively in the construction industry for precast parts, reinforced projected concrete, and industrial and airport pavements [3]. While adding a single fiber to concrete will only improve one component of its performance, combining with several fibers can increase the concrete's total performance. A specific admixture is mixed with multiple fiber sizes or types to create hybrid fiber concrete. By rationally integrating several fiber types in a concrete matrix, hybrid fiber reinforced concrete's performance can be enhanced on several levels. The cost can also be decreased by using cheaper synthetic fibers instead of costly metal ones [4]. It reduces crack widths and improves ductility, durability, shear resistance, and fracture resistance when used to restore structural elements [5]. The corrosion of steel bars caused by chloride ion action is the primary cause of the property degradation of structures in maritime settings. Therefore, the rapid corrosion of steel fibers may hasten the property degradation of marine engineering structures made of hybrid steel fiber/polypropylene fiber-reinforced concrete. The environmentally friendly fiber known as basalt fiber (BF) has been used more and more in concrete products in recent years. The process of creating BF involves melting basalt rock at high temperatures and pulling it into wires, which requires some energy. BF has strong mechanical properties and is resistant to corrosion from acids and alkali. Numerous researchers claim that BF is also effective with cement-based materials. Therefore, by replacing steel fibers with BF, hybrid BF/PF-reinforced concrete (BPRC) can be used to increase the durability and fracture toughness of concrete under maritime settings [6].

Concrete is proportionately mixed with more than two different fiber kinds to produce a hybrid material that synergistically combines the benefits of each fiber type. Natural and synthetic fiber hybridization may improve the properties of concrete. In addition, it reduces the cost of concrete production [7]. The mechanical properties of concrete reinforced with basalt-macro polypropylene hybrid fibers with varying compressive strengths were the focus of a study conducted by Shi et al. The study looked at how fiber contents affected the slump, compressive strength, and flexural capacity of the concrete. The study introduced a new classification for failure processes and behavior in hybrid fiber-reinforced concrete. The results demonstrated that the hybrid concrete, which comprises 0.1% BF and 1% PPF, has better flexural strength, initial post-cracking strength, and energy absorption than regular concrete. The fracture energy of the concrete, which varied for concrete of different strengths, was the primary determinant of the post-cracking response [8].

The literature analysis indicates that the ideal amount of polypropylene and basalt fibers in concrete varies depending on the type of material. According to Wang et al., the mechanical properties of hybrid FRC were significantly improved by 0.15% BF and 0.0033% PPF [9]. Shi et al. reported similar results; however, they suggest varying fiber contents [10]. Smarzewski examined single BF, PF, and hybrid fibers independently in the same year and discovered that while hybridization increased flexural and tensile strength, it lowered compressive strength [11]. The addition of these fibers is intended to enhance the mechanical properties of concrete, and the use of M-sand is required to lessen the quantity of river sand utilized. In order to examine the flexural behavior of FRC and hybrid FRC beams, the current study concentrated on including single and hybrid fibers in addition to M-sand.

In order to examine the mechanical and flexural behavior of the hybrid FRC, the current work primarily concentrated on maintaining one fiber constant while varying the volume fraction of the other fiber by a different proportion. Furthermore, the materials utilized to prepare FRC are sustainable and environmentally beneficial. In addition to focusing on how it impacts flexural and compressive strength, the work provides a novel viewpoint on maintaining the volume fraction of polypropylene fiber as a constant and fluctuating proportion of basalt fibers in hybrid fiber reinforced concrete. It highlights how basalt fibers help with strength increase and fracture bridging, while polypropylene fibers improve strain distribution and post-cracking behavior.

2 Methodology

2.1 Materials

The binding material used herein is ordinary Portland cement. M-Sand is used as a fine aggregate and has a particle size of 4.75 mm and a fineness modulus of 2.8. M-Sand used in this study is fall in zone 3. The coarse aggregate is crushed granite with a maximum size of 20 mm and a minimum size of 12 mm. The specific gravity of coarse aggregate is 2.72. The properties of micro reinforcement materials of basalt and polypropylene fiber are given in Table 1. All the above ingredients were mixed with potable water and conplast SP – 430.

The hybrid fiber reinforced concrete mixture of M30 grade compositions designed are shown in Table 2, wherein CC represents the conventional concrete, CPPBF0 represents specimen with 0.25% PPF and 0% BF, CPPBF0.25 represents specimen with 0.25% PPF and 0.25% BF, CPPBF0.5 represents specimen with 0.25% PPF and 0.5% BF, CPPBF0.75 represents specimen with 0.25% PPF and 0.75% BF, CPPBF1.0 represents specimen with 0.25% PPF and 1% BF.

Table 1. Properties of Basalt and Polypropylene Fiber

Sl No.	Properties of Fiber	Basalt Fiber	Polypropylene Fiber
1.	Length	14 mm	12 mm
2.	Diameter	13μm	0.05 mm
3.	Specific Gravity	2.70	0.92
4.	Tensile Strength	2700 MPa	445 MPa
5.	Elongation at break	12.5%	18.25%
6.	Aspect Ratio	1076	240

Table 2. Hybrid Fiber Reinforced Concrete Mixture Compositions

Sl No.	Desig- nation	w/c Ratio	Water (kg/m^3)	SP (kg/m^3)	Cement (kg/m^3)	Coarse Aggregate (kg/m^3)	M- Sand (kg/m^3)	PPF (kg/m^3)	BF (kg/m^3)
1	CC	0.45	190	2.8	420	1257	685	0	0
2	CPPBF0								0
3	CPPBF0.25								5.12
4	CPPBF0.5	0.45	190	3.15	420	1257	685	5.12	10.25
5	CPPBF0.75								15.38
6	CPPBF1.0								20.51

As shown in Figure 1, to prepare the hybrid FRC mixture, first coarse aggregate and M-Sand were mixed for 30 s. Then, cement was added to the mixture and stirred for 2 min. Next PF and BF were added in turn and stirred for 2 min and 3 min respectively. Adding these fibers in stages reduces clumping by ensuring uniform distribution before adding water. High energy mixing and extended mixing time improved the dispersion of the fibers. Finally premixed SP with water was added and stirred for 2 min. immediately after mixing, the slump of the hybrid FRC mixture was tested using a slump cone, and the test results are listed in Table 3. Then, the hybrid FRC mixture was poured into 150 x 150 x 150 mm cubic molds, 150mm diameter and 300 mm height cylinder, 100 x 100 x 500 mm prismatic molds compacted on a vibrating table and 150 x 250 x 2200 mm beam moulds compacted using a vibrator machine. After 24 hrs of curing in room temperature, the specimens were demolded and continuously cured to the age of 28 days before the relevant mechanical properties were tested.

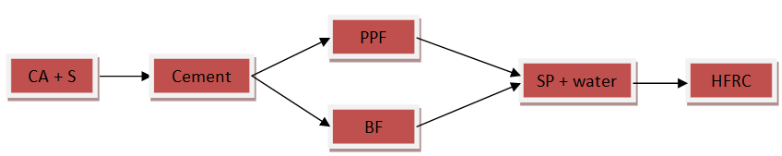


Fig 1. Schematic representation of hybrid FRC mixing Process

Table 3. Slump Value for Hybrid FRC Mixtures

Sl No	Mixture ID	Slump (mm)
1	CC	95
2	CPPBF0	78
3	CPPBF0.25	81
4	CPPBF0.5	82
5	CPPBF0.75	79
6	CPPBF1.0	77

2.2 Testing Methods

2.2.1 Compressive Strength Test

An electro-hydraulic pressure servo testing equipment was used to determine the compressive strength of HFRC specimens. The 150 mm x 150 mm × 150 mm specimen was put through its paces at a loading rate of 0.5 MPa/s. For each proportion of the HFRC combination, six specimens were tested—three for seven days and three for twenty-eight days—and the final experimental result was calculated by averaging the test results.

2.2.2 Flexural Strength Test

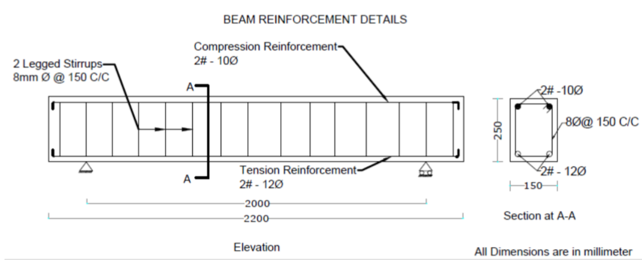
The prism specimens were tested in a loading frame that could support 100 kN of force. 150 x 150 x 500 mm specimens were used. At 400 mm, the test span was fixed. An average of six replicate specimens—three for seven days and three for twenty-eight days, respectively—were used to compute the results for each type of specimen. In order to evaluate the flexural strength of HFRC, a total of 36 specimens were used.

2.2.3 Modulus of Elasticity Test

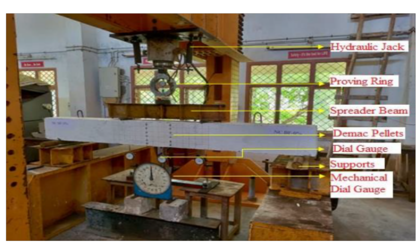
A digital CTM with a capacity of 2000 kN was used to apply an axial compressive load to the specimens. Until the maximal load was attained, deformations were observed using a dial gauge with a minimum count of 0.01mm at intervals of 10kN. The initial tangent modulus, or the slope of the stress-strain curve produced from the origin, was calculated in order to establish the modulus of elasticity. The modulus of elasticity of hybrid FRC was evaluated using a total of 36 specimens.

2.2.4 Flexural Behaviour of Beams

To analyze the flexural characteristics of hybrid FRC incorporated M-Sand. For the present study, two beams were cast for each mixture of CC, CPPBF0 and CPPBF0.75. Totally six number of beams were cast and tested. Two beams were tested in each set.



(a)



(b)

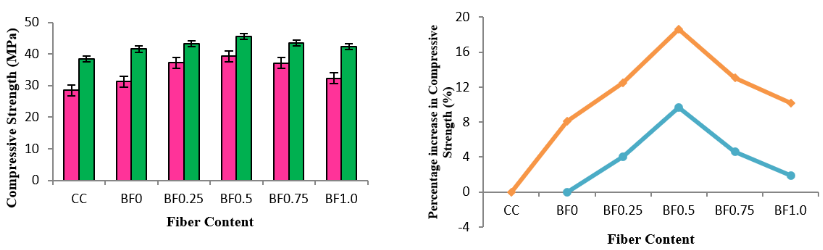
Fig 2. (a) Reinforcement Details of the Hybrid FRC Beams, (b) Loading Setup for the Beams

Figure 2**(a)** shows the reinforcement details of the proposed beam. Four-Point bending test was conducted in a static load condition. Prior to placing the beam specimen into the loading frame, the length of the beams is measured and divided into three equal parts, each section having the length of L/3. Then, grid patterns are delineated within the flexural region of the beam in order to figure out the crack pattern. In accordance with the length of the beam specimen, position adjustments are made to the hinged and roller supports in the loading frame. Following that, the beam is positioned over the loading frame. The load bearing capability of the simply supported beams was calculated using a two-point loading condition. Figure 2 **(b)** shows the laboratory loading setup for the beam. With the help of a hydraulic jack (500kN capacity and 0.83 kN least count), the load is applied progressively to the beam specimen via a steel spreader (I-section). The detection of deflection for 2.5kN load increment was observed by using dial gauges placed under the load and mid span with a least count of 0.01. As the applied load was progressively increased, the beam exhibited deflection and flexural cracks emerged along its span. The measurement of crack width and observation of crack propagation were also recorded, along with the identification of the failure mode for each test specimen. The crack width was measured with a precision of 0.02mm.

3 Results and Discussions

3.1 Compressive Strength

As shown in Figure 3, a variation in the compressive strength of concrete is incremental with the addition of basalt fiber till 0.5%. However, it starts to reduce beyond the addition of basalt fiber of 0.5% along with the polypropylene fiber of 0.25%. When it is in hybrid mode along with the pp fiber beyond 0.5% addition of basalt fiber reduces the compressive strength to an extent. This result differs from the observations made by Fu et al [6], the increase in compressive strength in their observation is because of the addition of supplementary cementitious materials. In the present study, the increase in the compressive strength till the addition of 0.5% is because of the confinement action that occurred in the matrix but after 0.5% there may be agglomeration of fibers, and it resulted in the reduction of the compressive strength.



(a) Compressive Strength (b) Percentage increase in Compressive Strength

Fig 3. Variation on the Compressive Strength of Hybrid FRC

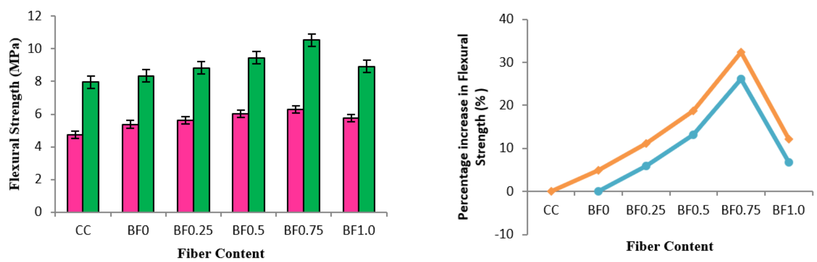
Mixture containing only polypropylene fiber showed an 8.12% increase compared to conventional concrete. When it comes to hybrid FRC mixture containing basalt fiber addition of about 0.25%, 0.5%, 0.75% and 1% showed an increase in compressive strength of about 12.49%, 18.60%, 13.11% and 10.20% respectively compared to the conventional concrete. Both single PP fiber and Hybrid FRC showed a significant increase in the compressive strength with M-Sand. Compared to the single PP fiber hybrid FRC containing BF of about 0.25%, 0.5%, 0.75% and 1% showed increases in compressive strength of about 4.04%, 9.70%, 4.62% and 1.92% respectively. Because of the addition of fibers, the failure patterns of all the FRC showed a similar pattern in that it failed with many cracks but didn't collapse but in the case of normal concrete, the specimens showed brittle failure.

The compressive strength of BFRC depends on the number of dispersed fibers. This is because the distribution of fibers is disturbed when the volume fraction of fibers in concrete is more than 0.3%, which results in a decline in compressive strength [1], in our study up to 0.5% compressive strength increased maybe this is because of hybridization with polypropylene fiber. However beyond 0.5% the strength starts to decrease, this is because of the higher percentage of basalt fiber concentration. Similar results have been obtained by Sun et al, in addition, they suggested optimum dosage of basalt fiber content may be between 0.05% to 0.5% [12]. Irrespective of fiber addition, variations in the compressive strength are also based on mix design criteria and utilization of superplasticizer, the addition of supplementary cementitious materials [13].

3.2 Flexural Strength

As shown in Figure 4, unlike compressive strength, flexural strength showed a higher increase when the basalt fiber addition reached 0.75% however beyond 0.75% flexural strength decreased. Adding BF and PF increases the flexural strength, which is in contrast to its influence on compressive strength. The increase in the flexural strength can be primarily due to the higher stiffness of the basalt fiber, the larger number of monofilaments and the superior bonding between basalt fiber and the matrix, which is the reason for basalt fiber to bridge the cracks. This is similar to the work conducted by the researchers Fu et al [6].

The mixture containing only polypropylene fiber showed a 4.90% increase compared to the conventional concrete. When it comes to hybrid FRC mixture containing basalt fiber addition of about 0.25%, 0.5%, 0.75% and 1% showed an increase in flexural strength of about 11.06%, 18.72%, 32.29% and 12.06% respectively compared to the conventional concrete. Both single PP fiber and Hybrid FRC showed a significant increase in the compressive strength with M-Sand. Compared to the single PP fiber hybrid FRC containing BF of about 0.25%, 0.5%, 0.75% and 1% showed an increase in compressive strength of about 5.87%, 13.17%, 26.11% and 6.83% respectively. Due to the large size difference, hybrid BF and PF can inhibit cracks during different fracture propagation stages. Basalt fiber is high modulus fiber and Polypropylene fiber is low modulus fiber, bridging the cracks at different stages when the specimen is subjected to flexural loading. Compared to the single PP FRC, hybrid FRC showed higher flexural strength. This is because of using different modulus of fiber, since PF is a low modulus fiber and BF is a high modulus fiber can able to bridge the crack at different stages of crack development. Adding more basalt fiber increases the flexural strength and PP fiber gives ample warning before failure of the specimen.



(a) Flexural Strength (b) Percentage increase in Flexural Strength

Fig 4. Variation on the Flexural Strength of Hybrid FRC

The variation in the growth ratio of the flexural strength of Hybrid FRC Compared with conventional concrete and single PP FRC is displayed in Figure 6. The growth ratio of flexural strength decreases when the basalt fiber addition is beyond 0.75%, which differs from the variation in the growth ratio of compressive strength. Thus, the increasing Basalt fiber addition weakens the influence of fibers on the flexural strength beyond 0.75%. However, this is in contrast to the results obtained by Jiaeng et al. They concluded their work, that when the basalt fibers percentage increased beyond 0.3% decreased the flexural strength compared to the mixtures containing fiber percentage below 0.3% [12].

3.3 Modulus of Elasticity

The Young's modulus values of conventional and fiber reinforced concrete are tabulated in Table 4. The test results also show a similar trend of the variation as compared to the compressive and flexural strength. A higher 'E' value was observed in the inclusion of 0.75% basalt fiber and 0.25% polypropylene fiber. Variation in the modulus of elasticity of mix containing basalt fiber of 0%, 0.25%, 0.5%, 0.75% and 1% is showing an increase of 8.82%, 13.15%, 15.20%, 17.38% and 12.37% compared to the conventional concrete.

Table 4. Modulus of Elasticity of Hybrid FRC Mixtures

Sl No	Mixture ID	Modulus of elasticity (GPa)
1	CC	29.35
2	CPPBF0	31.94
3	CPPBF0.25	33.21
4	CPPBF0.5	33.81
5	CPPBF0.75	34.45
6	CPPBF1.0	32.98

Based on the literature review, adding basalt fiber generally reduces the modulus of elasticity compared to conventional concrete, and this is because of the fact that the fibers added in the concrete act as voids and it leads to the reduction in the modulus of elasticity [12]. However the results obtained in the present study differ from the above outcome. It may be attributed to the hybridization of fibers, having different diameters can possibly reduce the voids created by the single fiber addition and leads to the increase in the modulus of elasticity of the FRC compared to the conventional concrete. It is similar to the works done by Prashanthi et al [14].

3.4 Flexural Load – Deflection Behaviour

The flexural load deflection behavior of conventional and hybrid FRC beams is shown in Figure 5. The effect of using fibers within the concrete mix is captured by comparing the flexural behavior of the hybrid fiber-reinforced concrete beams with that of the plain concrete specimen. The comparisons show that the addition of the basalt and polypropylene fibers showed a slight improvement in the load carrying capacity but improved both the cracking and post-cracking behavior of the reinforced-concrete beams with the same reinforcement ratio. Single PP fiber reinforced concrete beams show a little higher than conventional concrete however in the initial cracking stage there is a zigzag manner in the load deflection curve which is attributed to the low modulus PP fiber. The hybrid fiber reinforced concrete beam CPPBF0.75, which contains 0.25% polypropylene fiber and 0.75% basalt fiber provided a higher moment capacity than a single polypropylene fiber and conventional concrete. The percentage increase was found to be 8.33% and 19.33% for the beams CPPBF0 containing only polypropylene fiber of 0.25% and CPPBF0.75 containing both polypropylene fibers of 0.25% and basalt fiber of 0.75% respectively, compared to the CC, conventional concrete. The highest increasing percentage was 19.33% for hybrid fiber-reinforced concrete beam CPPBF0.75 and this could be attributed to the hybridization of low modulus and high modulus fiber. This beam showed a 10% increase in its moment capacity compared to the polypropylene fiber reinforced concrete of 0.25% around 9.33% increase was due to having high modulus and high tensile strength of basalt fiber, it starts bridging the crack during the initial loading and withstand till its ultimate strength and failed abruptly however it increased the moment capacity of the beam.

Both the low modulus and high modulus fiber bridge the crack at the different stages of loading and gradually increase the hardening stage of the concrete beam compared to both conventional and only polypropylene fiber of 0.25%. The synthetic FRC beam was capable of sustaining more loads with higher deflection. The same behavior was reported by Farid et al [2]. Moreover, the addition of basalt fibers to the concrete helps control the compression failure of the fiber-reinforced concrete beams by means of the fiber bridging effect. This can be considered the main reason for the increase in flexural capacity noticed in the fiber-reinforced concrete beams.

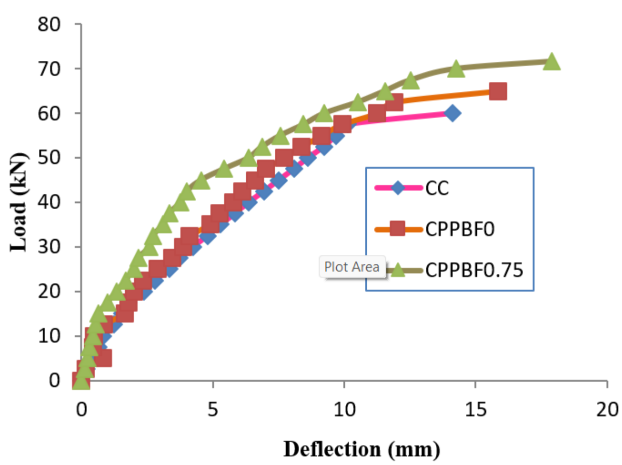


Fig 5. Load Vs Deflection curves of Conventional and FRC beams

The cracking load at which the first flexural crack appeared was recorded during the experiment. For all fibered beams, the first crack appeared at higher loads than the control beam. The fiber bridging action, which prevented the crack from growing, was attributed to this. The first cracking loads of 12.5 kN, 15 kN, and 20 kN were noted in CC, CPPBF0, and CPPBF0.75. The hybrid fiber-reinforced beam had the highest first fracture loads, which were 0.75 times that of the CPPBF0 and 1.6 times that of the CC beams. Therefore, it was determined that the inclusion of polypropylene fibers and basalt fiber had a greater impact on the first cracking load in the mix CPPBF0.75 displayed a larger cracking load than the control beams and CPPBF0. This study shows that hybrid fiber reinforcement provides higher ductility and energy absorption capability compared to traditional concrete or single-fiber reinforced systems. The results show that the fibers are optimally balanced to improve load-carrying ability and reduce unexpected failure.

The addition of fibers increased the flexural strength of concrete, propagation of cracks, increased ductility by showing ample warning, and improved ultimate load and failure modes [9].

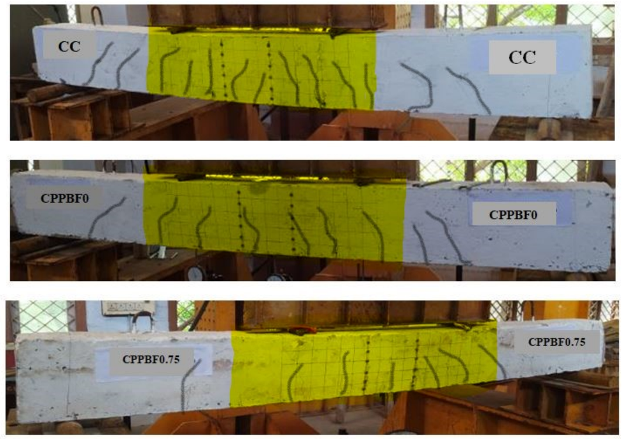


Fig 6. Crack Pattern of Conventional and FRC beams

From Figure 6, it is observed that flexural failure in all three sets of beams. Initially, the vertical cracks were observed in midspan and gradually appeared near the support. The maximum number of cracks observed in the conventional concrete beam specimen and crack width is also high when compared to the other fiber reinforced concrete. The maximum crack width of 0.35mm, 0.3mm, 0.25mm and 9, 6, 5 numbers of cracks were observed in the CC, CPPBF0 and CPPBF0.75 beam specimens respectively.

Hybridization of basalt and polypropylene fiber effectively bridged the cracks and showed better performance under flexure by showing 5 no. of cracks with a maximum width of 0.25mm. It is also observed that the bond between the fiber and concrete effectively prevents the propagation of the cracks.

4 Conclusion

This study investigates the synergistic effects of polypropylene fibers (PPF) and basalt fibers (BF), a combination that has received little attention. While polypropylene fibers improve ductility, crack resistance, and impact strength, basalt fibers are renowned for their great tensile strength, thermal stability, and environmental friendliness. By utilizing the complementing qualities of both fibers, this special hybridization maximizes the performance of concrete. The study presents an environmentally acceptable method of enhancing concrete performance by using basalt fibers, a material made from naturally occurring volcanic rock. The combination with inexpensive and lightweight polypropylene fibers provides a creative way to create long-lasting and environmentally friendly building materials.

The basalt fiber can be used in place of steel fiber, which is more expensive and prone to rust. Like steel fiber, basalt fiber improves the concrete's flexural strength. Compressive strength exhibits a declining trend beyond 0.5%. This behavior can be the result of irregular dispersion that happened in the concrete member while the polypropylene fibers were present. The tendency of basalt fiber under compression is also impacted because the behavior of concrete under compression differs from that under tension.

The outcomes of the experimental study are indicated below:

1. As the volume proportion of basalt fiber in fiber-reinforced concrete increases, its compressive and flexural strength also increases. However, after 0.5% basalt fiber inclusion, the rise in compressive strength becomes less noticeable. When the percentage of basalt fiber surpasses 0.75%, a comparable pattern is seen in flexural strength.
2. There are both beneficial and detrimental synergistic effects when the two fiber types are combined. The Hybrid FRC mix had a positive effect on hybridization when the volume fractions were 0.75% of basalt fiber and 0.25% of polypropylene fiber (PPF). Comparing the fiber-reinforced concrete with only polypropylene fiber, the compressive strength, and flexural strength increased by 4.62% and 26.11%, respectively.

3. The modulus of elasticity of the hybrid FRC mix of CPPBF0.75 showed an increase of 17.35% when compared to the conventional concrete.
4. Results of four point bending of all three sets of beams also indicate that the hybrid mix of CPPBF0.75 beam performs superior when compared to the CC and CPPBF0 beams. Particularly the cracking behaviour of CPPBF0.75 beams in terms of crack width and number of cracks were effectively reduced to 0.25mm and 5 from 0.35mm and 10 respectively compared to the CC beams.
5. The addition of basalt fiber along with the polypropylene fiber prevented the propagation of cracks to a certain extent compared to CC and CPPBF0 beams. All the beam specimens showed a flexural failure mode.

Acknowledgements

The study is part of the research conducted by the first author towards a Ph.D. dissertation.

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