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Performance Evaluation of Fiber Reinforced Concrete Using Basalt, Banana and Polypropylene Fibers

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Abstract:
This study investigates about the adding fibers specifically, polypropylene, banana, and basalt can improve the mechanical and durability properties of concrete. Fiber-reinforced mixes with 0.25% and 0.50% fiber by volume were compared to a control mix devoid of fibers. According to experimental data, fiber-reinforced concrete (FRC) had better qualities. For example, the compressive strength increased by 12%, from 32.5 MPa in the control mix to 36.4 MPa with 0.50% basalt fiber. Tests for durability, such as the Rapid Chloride Penetration Test, showed notable improvements: water absorption dropped from 5.2% to 4.2%, indicating decreased porosity, and impact resistance increased significantly from 18 blows for standard concrete to 45 for basalt fiber concrete. Furthermore, FRC retained 92% of its initial strength at 200°C heat testing, while regular concrete only retained 89%. In terms of strength, stiffness, and durability, basalt fiber at a 0.50% concentration continuously performed better than other fibers. Overall, fiber reinforcement greatly increased the durability and sustainability of concrete, indicating that it is appropriate for both structural and non-structural uses, such as industrial floors and pavements. The effectiveness of basalt fiber reinforced concrete for high-performance construction applications was confirmed by notable improvements of 12% in compressive strength, 27% in tensile strength, 41% in flexural strength, a 34% decrease in permeability, and more than 150% in impact resistance.

Keywords:
Fiber Reinforced Concrete (FRC), Compressive Strength, Flexural Strength, Durability.

1. Introduction:

Because of its carbon footprint, concrete which is made up of cement, aggregates, and water raises environmental issues, especially in poor countries. This can be lessened by employing nanotechnology with materials like rice husk ash and municipal solid waste incineration ash, as well as by replacing cement with industrial byproducts like fly ash and slag. Traditional concrete is widely used; however, it has poor tensile strength and brittleness, which can cause unexpected failure. By adding different fibers that increase toughness and crack resistance, FRC increases tensile strength and ductility [1-3].

Mechanisms like energy dissipation and crack bridging enable FRC better regulate microcracks and prolong the life of concrete buildings. This composite material is essential for addressing the rapid increase in cement production and the greenhouse gas emissions that go along with it, and it may be used in many other construction components. FRC is a major development in concrete technology since improved formulations utilizing polypropylene fibers and mineral admixtures result in more resilient and sustainable concrete solutions.

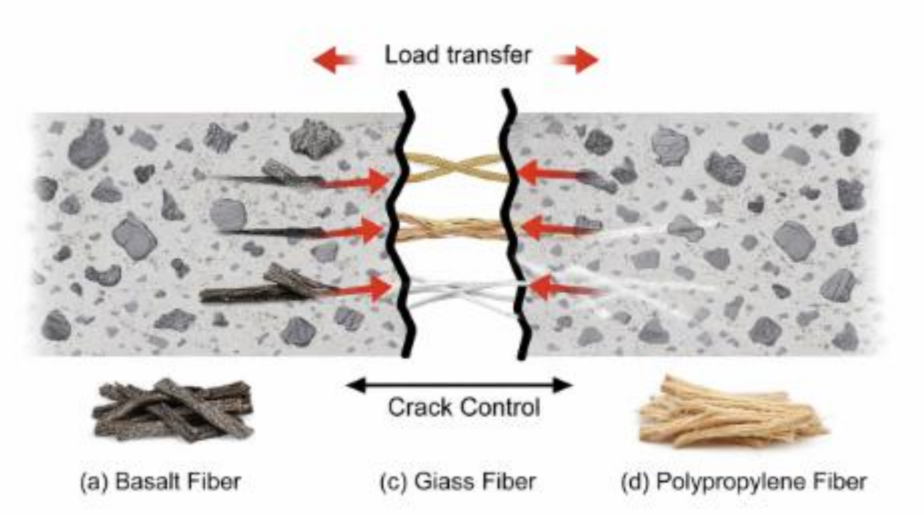

Figure 1 Fiber-reinforced concrete's crack bridging mechanism

Higher performance demands for concrete structures highlight the need for improved strength, durability, and sustainability. Conventional concrete is prone to brittle failure and low crack resistance, impacting maintenance costs. While FRC research has focused on steel and synthetic fibers, basalt fiber reinforced concrete (BFRC) remains less studied despite its advantages like high tensile strength and corrosion resistance. Current studies often overlook critical serviceability factors. A structured experimental study is needed to evaluate the flexural behavior of basalt fiber-reinforced concrete against polypropylene and banana fibers, employing M30 grade concrete with two fiber volume fractions (0.25% and 0.50%). Key mechanical characteristics such as compressive, tensile, and flexural strength will be assessed after 28 days of curing to determine the optimal fiber type and content for structural performance [10-11].

Because FRC can lessen the brittleness of conventional concrete, it has attracted a lot of scientific interest. To improve the mechanical qualities and longevity of concrete, numerous researches have investigated various fiber materials, volumes, and shapes. While basalt fibers are still underdeveloped despite their potential, steel fibers have been the focus of most research. The critical significance of fibers in crack propagation and post-cracking behavior was demonstrated by Bentur and Mindess (2007), who noted aspects like aspect ratio and fiber-matrix bonding [5]. According to Li et al. (2001), ACI Committee 544 (2009) discovered that fibers increase toughness and energy absorption under flexural stresses, changing concrete failure from brittle to ductile [12]. Although they only slightly increase strength, polypropylene fibers are known to lessen plastic shrinkage cracking (Banthia and Gupta, 2006; Yao et al., 2003) [4].

The drawbacks of conventional concrete, particularly its poor tensile strength and brittle fracture, are addressed with FRC [7-9]. Although steel fibers improve strength and ductility, their usage in severe environments is limited by problems like weight and corrosion. Glass fibers enhance flexural performance but present durability issues, whereas synthetic fibers like polypropylene successfully reduce microcracking but offer negligible strength benefits. According to recent studies, natural fibers such as banana fibers are more ductile and sustainable, but they have trouble with long-term performance because of water absorption and unpredictability. Research indicates that BFRC performs better than other FRC kinds in a number of mechanical parameters, and basalt fibers are becoming more and more popular due to their high tensile strength and endurance. Nevertheless, there aren't many thorough comparative investigations with various fiber kinds at comparable volume percentages. By examining basalt, banana, and polypropylene fibers in concrete at 0.25% and 0.50% volume fractions, this work seeks to close these gaps by providing important information on flexural strength and fracture behavior for environmentally friendly building.

2. Materials & Methods

In order to assess the mechanical and serviceability performance of fiber reinforced concrete, the chapter describes the materials, properties, mix ratios, specimen preparation, curing procedure, and testing methods. It seeks to evaluate and contrast how different volume fractions of polypropylene, banana, and basalt fibers affect the behavior of concrete.

2.1 Materials

This section describes the materials utilized in the experimental program's concrete construction, emphasizing particular kinds and their characteristics.

2.1.1 Cement

The Ordinary Portland Cement (OPC) used was 53-grade, compliant with IS 12269:2013, lump-free, and kept dry. The specific gravity of 3.15, standard consistency of 31%, starting set time of 35 minutes, final set time of 520 minutes, and fineness of 6% are important characteristics.

2.1.2 Fine Aggregate

Natural river sand was completely dry, pure, and devoid of organic contaminants in accordance with IS 383:2016's Zone II grading. Specific gravity of 2.65, fineness modulus of 2.72, water absorption of 1.10%, and bulk density of 1620 kg/m³ are among the observed properties.

2.1.3 Coarse Aggregate

According to IS 383:2016, the coarse aggregate was made out of crushed angular granite with a maximum nominal size of 20 mm. Its bulk density is 1550 kg/m³, its specific gravity is 2.7, its water absorption is 0.80%, and its aggregate impact value is 18%.

2.1.4 Water

For efficient cement hydration, strength development, and durability, the use of potable water free of contaminants was stressed. The formation of calcium silicate hydrate (C–S–H) gel requires water.

2.1.5 Basalt Fibers

Made by melting natural basalt rock, basalt fibers have excellent chemical resistance and great tensile strength. With dimensions of 12 mm in length, 14 μm in diameter, 2.7 g/cm³ in density, 3800 MPa in tensile strength, and 85 GPa in elastic modulus, they greatly improve the flexural strength and ductility of the concrete.

Figure 2 Basalt fibers

2.1.6 Banana Fibers

These biodegradable fibers, which are derived from banana plants, promote sustainable practices by adding value to waste. High water absorption and inconsistent mechanical characteristics are problems, even if they increase ductility and crack resistance. Its dimensions are 20 mm in length, 1.35 g/cm³ in density, 400 MPa in tensile strength, and 25 GPa in elastic modulus.

Figure 3 Banana fibers

2.1.7 Polypropylene Fibers

These synthetic fibers are inexpensive and chemically inert. They enhance serviceability and aid in preventing cracking without appreciably lowering compressive strength. Its length of 12 mm, density of 0.91 g/cm³, tensile strength of 500 MPa, elastic modulus of 4 GPa, and melting point of 160 °C are among its notable characteristics.

Figure 4 Polypropylene fibers

2.2 Casting and Curing of sample specimens

In order to attain M25 grade characteristic strength, the study concentrated on creating a concrete mix that complies with IS 456:2000 and IS 10262:2019 criteria. The proportions of cement, fine aggregate, and coarse aggregate in the control mix were determined to be 1:1.65:2.95, with a water-to-cement ratio of 0.45. To ensure consistency across all fiber-reinforced mixes, fibers were added at volume fractions of 0.25% and 0.50% without changing the cement content. Every mold was carefully cleaned and lubricated before casting. The ingredients were precisely weighed and then mixed using a tilting drum concrete mixer. The cement, fine aggregate, and coarse aggregate were dry mixed for around two minutes before the fibers were added gradually to achieve uniform distribution and avoid clumping. After that, water was gradually added until the mixture was homogenous. The mixes were put into ready-made molds, crushed with a table vibrator to release trapped air, and then the specimens' surfaces were leveled with a trowel.

Table 1 Test Specimen details

S. No	Test	Specimen Type	Size (mm)
1	Compressive Strength	Cube	150 × 150 × 150
2	Split Tensile Strength	Cylinder	150 dia × 300 height
3	Flexural Strength	Beam	100 × 100 × 500
4	RCPT	Cylinder (disc)	100 dia × 50 thick
5	Water Absorption	Cube	150 × 150 × 150
6	Impact Resistance	Disc	150 dia × 63.5 thick
7	UPV Test	Cube	150 × 150 × 150
8	Flexural Fatigue	Beam	100 × 100 × 500
9	Thermal Resistance	Cube	150 × 150 × 150

Table 2 Specimen details

Mix ID	Fiber Type	Fiber Volume Fraction
PC	Plain Concrete	0%
BF-0.25	Basalt Fiber	0.25%
BF-0.50	Basalt Fiber	0.50%
BNF-0.25	Banana Fiber	0.25%
BNF-0.50	Banana Fiber	0.50%
PPF-0.25	Polypropylene Fiber	0.25%
PPF-0.50	Polypropylene Fiber	0.50%

Figure 5 Casting and curing of specimens

3. Results for tests

3.1 Workability test

The slump cone test, which measures uniformity and placement ease, was used to assess the workability of new concrete mixtures in compliance with IS 1199:2018. The goal of testing right away after mixing was to reduce workability loss over time. The cone was filled with three layers of concrete, and the height reduction was measured to get the slump values.

Excellent workability for conventional reinforced concrete applications with PC was demonstrated by the greatest slump of 85 mm. Conversely, because of higher internal friction, fiber-reinforced blends showed fewer slumps. Because of the stiffness and roughness of basalt fibers, slump reductions of roughly 15% and 29% were seen in basalt fiber reinforced concrete at fiber percentages of 0.25% and 0.50%, respectively. Due to the irregular texture and water absorption of the fibers, banana fiber blends showed the greatest reductions in slump, with reductions of 20% (BNF-0.25) and 39% (BNF-0.50). On the other hand, because of the smooth texture and hydrophobic nature of the fibers, polypropylene fiber reinforced concrete maintained workability better, with slump reductions restricted to 12% and 24% for 0.25% and 0.50% fiber levels, respectively.

Figure 6 Slump cone test

Table 3 Workability test results

Mix ID	Fiber Type	Fiber Volume Fraction (%)	Slump (mm)
PC	Plain Concrete	0	85
BF-0.25	Basalt Fiber	0.25	72
BF-0.50	Basalt Fiber	0.5	60
BNF-0.25	Banana Fiber	0.25	68
BNF-0.50	Banana Fiber	0.5	52
PPF-0.25	Polypropylene Fiber	0.25	75
PPF-0.50	Polypropylene Fiber	0.5	65

2.2 Mechanical tests

2.2.1 Compressive strength

After regular size inspections and seven and twenty-eight days of curing, the cube examples were put through compression testing. In order to ensure consistent load application at a rate of roughly 0.6 MPa/s till failure, each was tested in a compression device. Compressive strength was computed by dividing the greatest load at failure by the cross-sectional area of the specimen and averaging the results from three specimens. The compressive strength data for several fiber-reinforced combinations are displayed in figure 8. Because basalt fibers can stop crack propagation under compressive stress, basalt fiber-reinforced concrete (BFRC) showed the most notable strength increase, with BF-0.50 demonstrating a 12% improvement over plain concrete. On the other hand, banana fiber combinations showed moderate gains because of improved stress redistribution, while polypropylene fibers had little effect because of their low elasticity. In all combinations, the addition of fibers had a little but positive impact on compressive strength.

Figure 7 Compressive strength test

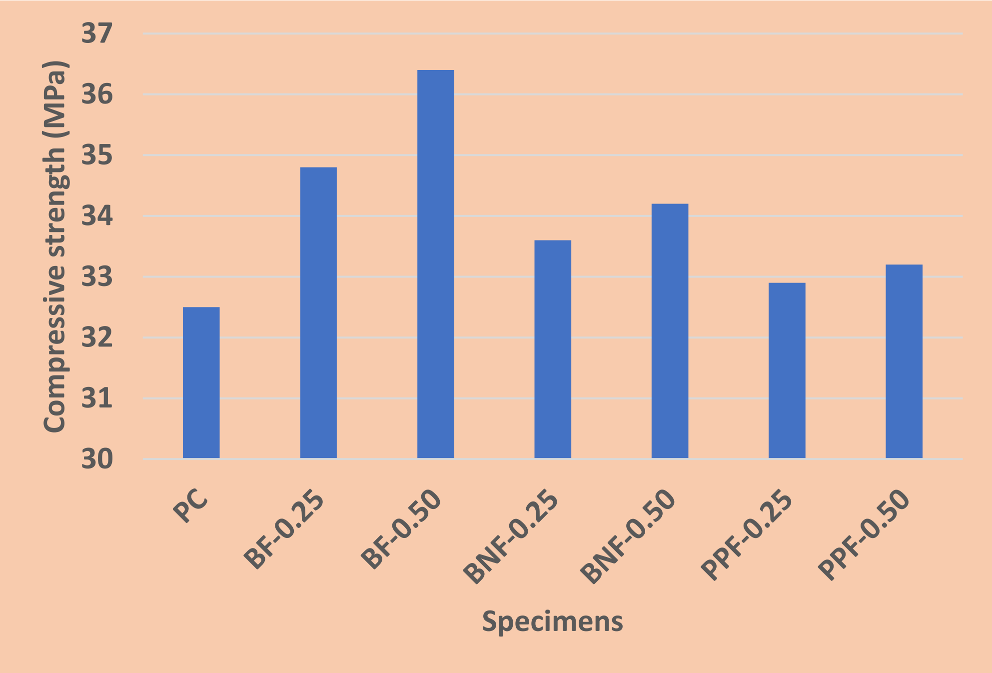

Figure 8 Compressive strength outcomes

2.2.2 Split Tensile Strength

After curing, the cylindrical specimens were dried and compressed horizontally between machine platens using plywood strips to guarantee even load distribution. The split tensile strength was determined using established methods based on the maximum load recorded after a gradual load was applied until a splitting failure occurred along the cylinder's vertical diameter. Three specimens average tensile strength was used as a representative value.

Split tensile strength was notably improved by adding fiber; BF-0.50 outperformed PC by 27.6%, while BFRC showed the greatest improvement. The fracture-bridging capacity of basalt fibers, which successfully stops tensile crack opening, is responsible for this improvement. Banana fibers also showed promise as an environmentally friendly reinforcement by increasing tensile strength. On the other hand, rather than significantly boosting strength, polypropylene fibers mainly helped with fracture management.

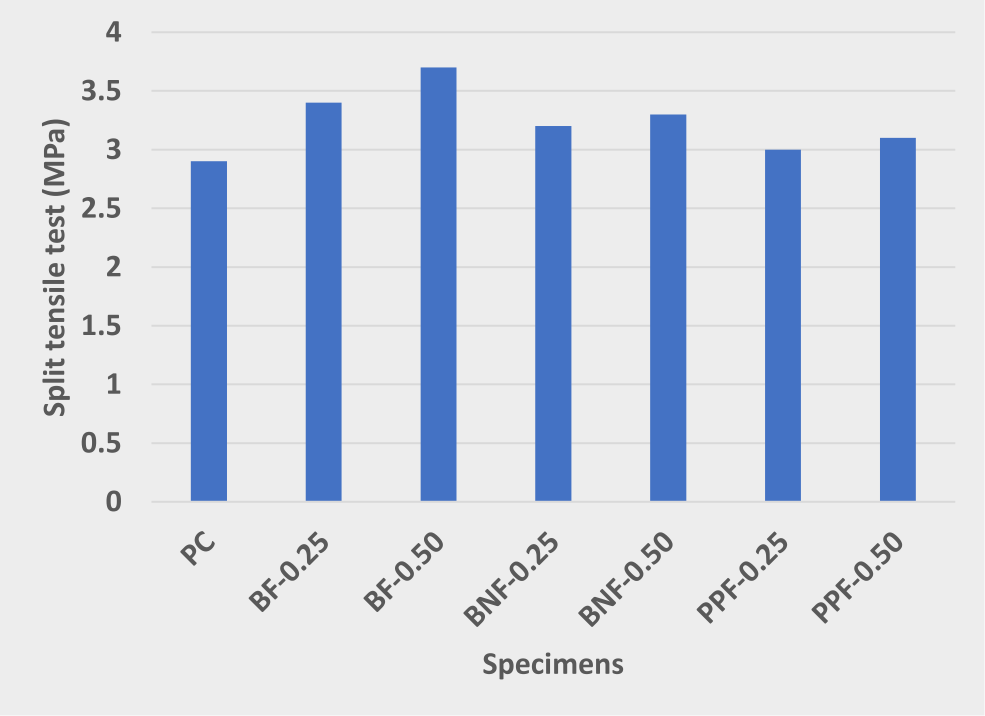

Figure 9 Split tensile test outcomes

Figure 10 Split tensile test

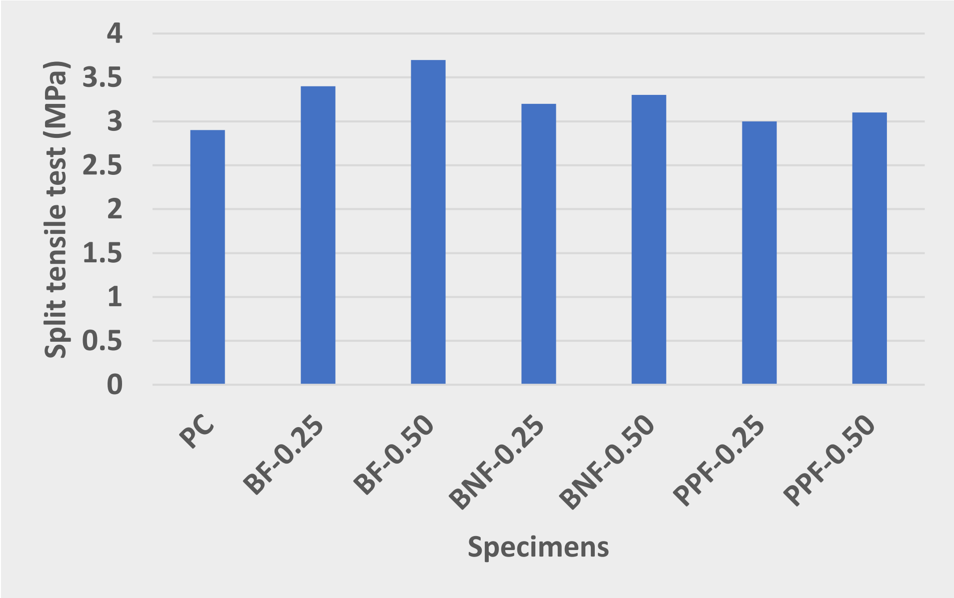

Figure 11 Split tensile test outcomes

3.2.3 Flexural test

By applying a force at the mid-span of prism specimens placed on supports 400 mm apart, the two-point loading method was used to assess flexural strength. The force was delivered consistently until failure occurred, and the specimens were meticulously oriented to guarantee uniform load distribution. In order to calculate flexural strength based on the failure load and specimen dimensions, the greatest load that the specimens could support was noted. Average values were obtained from three specimens per blend.

Because of their high tensile strength and elastic modulus, basalt fibers demonstrated a 41.5% increase in performance, with flexural strength showing the most notable improvement among mechanical characteristics. Additionally, a noteworthy improvement in flexural strength was demonstrated by banana fiber combinations, suggesting their efficacy in crack filling. On the other hand, polypropylene fiber combinations only slightly improved overall load-bearing capacity, mainly by improving post-crack resistance.

Figure 12 Flexural test

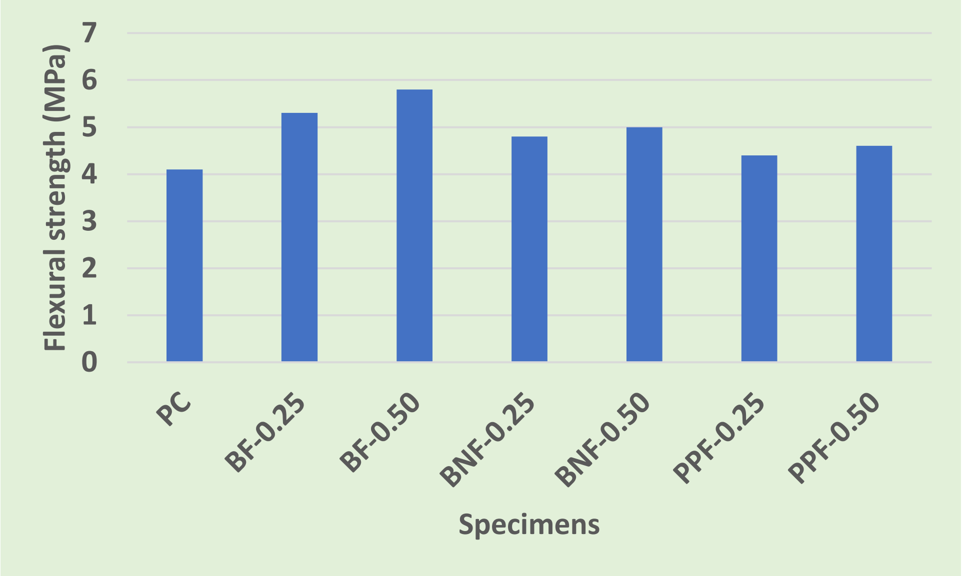

Figure 13 Flexural strength test

2.2.3 Rapid Chloride Penetration test (RCPT)

The RCPT was used to assess concrete's resistance to chloride ion penetration. To guarantee complete pore saturation, cylindrical specimens that had been cured for 28 days were vacuum-saturated and then divided into discs. A DC voltage of 60 V was applied to each specimen for six hours while it was placed between two testing chambers, one holding a 0.3N sodium hydroxide (NaOH) solution and the other a 3% sodium chloride (NaCl) solution. The total charge in coulombs could be calculated because the current was measured every thirty minutes. Improved durability is indicated by lower charge levels, which also show higher resistance to chloride penetration.

According to the findings, adding fiber considerably lowers the penetration of chloride ions; for PC, a charge of 3200 coulombs indicates moderate permeability. BF-0.50 showed the lowest charge value of 2100 coulombs among fiber-reinforced mixes, indicating minimal permeability and a 34% reduction. The strong bonding and crack-bridging qualities of basalt fibers, which reduce pore connectivity, are responsible for this enhancement. Banana fiber mixes demonstrated a mild improvement, while polypropylene fibers also provided a small improvement since they were better at managing cracks. Overall, by reducing chloride intrusion, adding fibers to concrete compositions increases durability.

Figure 14 RCPT setup

Table 4 RCPT test results

Mix ID	Charge Passed (Coulombs)	Chloride Permeability
PC	3200	Moderate
BF-0.25	2600	Moderate
BF-0.50	2100	Low
BNF-0.25	2800	Moderate
BNF-0.50	2400	Moderate
PPF-0.25	2900	Moderate
PPF-0.50	2500	Moderate

2.2.4 Water Absorption Test

A standardized water absorption test was used to evaluate the porosity and permeability of concrete. 150 mm^3 concrete cube specimens were cast and allowed to cure for 28 days. Following curing, they were dried for a full day at 105°C before being chilled in a desiccator to get a stable weight. Before each specimen was submerged in clean, room-temperature water for a day, its dry weight (W_1) was measured. After wiping off the surface water, the saturated weight (W_2) was calculated. The formula Water Absorption (%) = $[(W_2 - W_1) / W_1] \times 100$ was used to determine the water absorption percentage. Because fiber-reinforced concrete has better matrix densification and efficient fracture control, denser concrete with lower water absorption ratings has fewer voids and is more durable.

The findings of the water absorption test show that fiber-reinforced concrete has lower water absorption values than ordinary concrete. The BF-0.50 blend had the lowest absorption rate at 4.2%, indicating a roughly 19% decrease, while the control mix had the highest absorption rate at 5.2%. This suggests that the fiber addition improves matrix densification and decreases voids in the concrete. Banana fiber combinations demonstrated a moderate improvement in water absorption, while polypropylene fiber blends provided a minor improvement. The fibers' contribution to the concrete's increased durability and impermeability is highlighted by the observed decrease in water absorption.

Figure 15 Water absorption of specimens

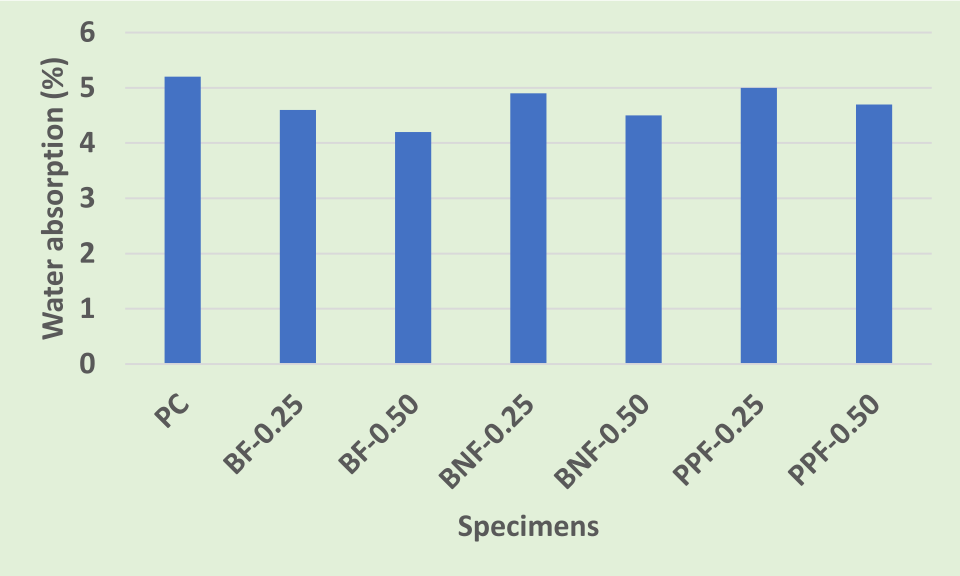

Figure 16 Water absorption outcomes

2.2.5 Impact Resistance test

The purpose of the impact resistance test was to evaluate concrete's ability to tolerate frequent, sudden impacts. A drop-weight impact device was used to examine specimens that were 150 mm in diameter and 63.5 mm thick after they had been cured for 28 days. A hammer was dropped to exert stress while a steel ball was positioned on top of the specimen. N_2 denoted the first cracking, and N_2 the blows that resulted in complete collapse. Fiber-reinforced concrete exhibits increased toughness because fibers bridge cracks, and the differential (N_2 - N_1) shows post-cracking energy absorption. In comparison to the control mix, which exhibited brittle behavior with just 12 blows for cracking and 18 for failure, test findings demonstrated that fiber-reinforced concrete had much better energy absorption. BF-0.50, on the other hand, needed 28 strikes for the first crack and 45 for failure, showing a more than 150% increase in impact resistance, which is explained by fiber bridging postponing the formation and growth of cracks. Impact resistance was positively impacted by both polypropylene and banana fiber blends, demonstrating that fibers improve overall toughness and dynamic stress resistance.

Table 5 Impact Test Results

Mix ID	Blows to First Crack (N_1)	Blows to Failure (N_2)
PC	12	18
BF-0.25	20	32
BF-0.50	28	45
BNF-0.25	18	30
BNF-0.50	22	36
PPF-0.25	16	28
PPF-0.50	19	34

2.2.6 Ultrasonic Pulse Velocity (UPV) test

Using 150 mm cube specimens, the UPV test is a non-destructive technique used to evaluate the consistency, integrity, and quality of concrete. Specimen surfaces were cleaned and a coupling medium, such as gel or grease, was added to guarantee efficient ultrasonic wave transmission. Transducers were positioned on opposing sides of the specimen in the direct transmission mode, and an ultrasonic pulse was sent from the transmitter to the receiver via the concrete. By measuring the time it took for the pulse to travel through, an electronic timing device made it possible to calculate the pulse velocity using the formula: velocity = path length / time.

Higher velocity numbers represent superior concrete with fewer internal flaws, whereas lower values suggest possible voids or cracks. According to the test results, fiber-reinforced concrete has better internal quality and uniformity than traditional concrete. The BF-0.50 blend demonstrated an amazing velocity of 4.5 km/s, which was ascribed to decreased internal voids and enhanced matrix integrity from fiber integration, while the control mix attained a velocity of 4.1 km/s, certifying it as high grade. Additional evidence that fiber reinforcement improves concrete's structural stability was found in combinations containing polypropylene and banana fibers.

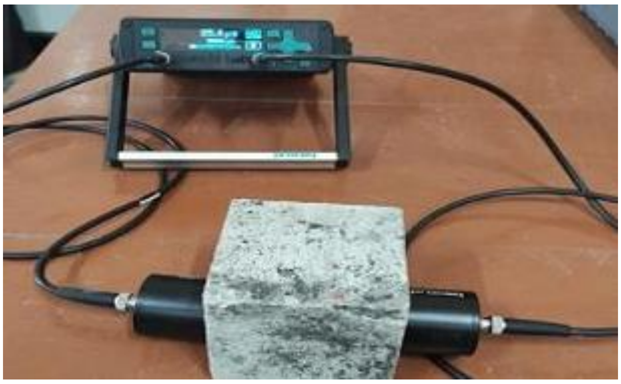

Figure 17 UPV test

Table 6 UPV Results

Mix ID	Pulse Velocity (km/s)	Quality of Concrete
PC	4.1	Good
BF-0.25	4.3	Good
BF-0.50	4.5	Excellent
BNF-0.25	4.2	Good
BNF-0.50	4.3	Good
PPF-0.25	4.2	Good
PPF-0.50	4.3	Good

3.2.7 Thermal Resistance test

The purpose of the thermal resistance test was to assess how concrete would react to elevated temperatures. In order to prevent thermal shock, 150 mm^3 specimens were cured for 28 days, dried, and then progressively heated to 200°C in a hot air oven at a rate of 5 to 10°C per minute. The specimens were let to cool naturally after being kept at this temperature for two hours. The heated specimens were compared to their initial strength in order to determine the residual compressive strength and percentage strength reduction.

The fragility of the PC was demonstrated by a strength drop of 10.8%, from 32.5 MPa to 29.0 MPa. Fiber-reinforced blends, on the other hand, only saw an 8% to 10% decrease in strength. In particular, the remarkable thermal stability and bonding qualities of basalt fibers that prevent micro-cracking during heating allowed the BF-0.50 blend to maintain over 92% of its initial strength with only an 8.0% drop. The strength losses for the other mixes, BNF-0.50 and PPF-0.50, were roughly 7.9% and 8.1%, respectively. variances in material properties like stiffness and thermal stability were identified as the cause of the minor variances in fiber performance. Moisture evaporation and the creation of microcracks, which fibers aid in bridging to maintain structural integrity, were the main causes of the strength drop in all blends. Overall, the findings unequivocally show that, in mild heat circumstances, fiber-reinforced concrete outperforms conventional concrete, making it more appropriate for high-temperature applications.

Figure 18 Hot air oven used for thermal resistance testing

Table 7 Thermal Resistance Results

Mix ID	Original Strength (MPa)	Residual Strength (MPa)	Strength Retention (%)	Strength Reduction (%)
PC	32.5	29.0	89%	10.8%
BF-0.25	34.8	31.5	91%	9.5%
BF-0.50	36.4	33.5	92%	8.0%
BNF-0.25	33.5	30.2	90%	9.9%
BNF-0.50	34.2	31.5	92%	7.9%
PPF-0.25	32.8	29.8	91%	9.1%
PPF-0.50	33.2	30.5	92%	8.1%

3. Conclusions

The mechanical and serviceability characteristics of Polypropylene Fiber Reinforced Concrete, Banana Fiber Reinforced Concrete, and Basalt Fiber Reinforced Concrete were compared to regular concrete in the experimental investigation. Important results show that adding fibers greatly improves performance in a number of areas:

- Compared to the control mix's 32.5 MPa, the compressive strength of BF-0.50 was significantly higher, rising by 12% to 36.4 MPa. While PPFRC demonstrated only slight improvements (33.2 MPa), BNFRC showed notable improvement (34.2 MPa).
- The split tensile strength of BF-0.50 was 3.7 MPa, which is 27% greater than the control mix's 2.9 MPa. With strengths of 3.3 MPa and 3.1 MPa, respectively, banana and polypropylene fibers also made a positive contribution.
- The most notable improvement was in flexural strength, where BF-0.50 increased from 4.1 MPa in regular concrete to 5.8 MPa. Improved structural performance was demonstrated by polypropylene blends reaching 4.6 MPa and banana fiber mixes reaching 5.0 MPa.
- As fiber content rose, workability decreased and slump values decreased. Because of increased friction and fiber absorption, the lowest was found in BNFRC at 52 mm.
- Rapid Chloride Penetration tests revealed that BF-0.50 had lower permeability (2100 coulombs) than the control mix (3200 coulombs), improving resistance to chloride intrusion. Additionally, water absorption decreased from 5.2% in the control mix to 4.2% in BF-0.50.
- Compared to the control mix, BF-0.50 demonstrated better energy absorption, withstanding more than 150% more impacts. BNFRC showed improved toughness by withstanding 36 hits.
- The Ultrasonic Pulse Velocity test revealed improved internal consistency, with BF-0.50 achieving 4.5 km/s as opposed to 4.1 km/s for the control mix.
- By incorporating fiber, the behavior changed from brittle to ductile under load, resulting in better fracture management with smaller cracks and enhanced ductility.
- Because larger dosages negatively impacted workability, the optimal fiber content for balance was determined to be 0.50%.
- Fiber-reinforced mixtures lost 8% to 10% of their strength when exposed to 200°C, although BF-0.50 showed the least amount of loss (8.0%), demonstrating improved heat resistance.

Overall, polypropylene fibers were useful for crack management and serviceability, banana fibers provide sustainable benefits with negligible strength gains, and basalt fibers demonstrated outstanding performance in strength and durability.

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