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Experimental Study on Flexural Behavior of High Strength Concrete Beams with Hybrid Fibers

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Abstract High-strength concrete (HSC) exhibits excellent compressive strength but suffers from brittle failure under flexural loading, limiting its ductility and crack resistance. The incorporation of hybrid fibers has emerged as an effective strategy to overcome these limitations by enhancing post-cracking behavior and energy absorption capacity. This study investigates the flexural performance of HSC beams reinforced with different combinations of steel fibers, polypropylene fibers, and basalt fibers. A systematic experimental program was conducted on reinforced concrete beams with varying fiber dosages and hybrid ratios. The parameters studied include first crack load, ultimate load, load–deflection response, crack propagation, ductility index, stiffness degradation, and flexural toughness. Comparative analysis with control specimens highlights the significant role of hybrid fibers in improving structural performance. The results indicate that beams with optimal hybrid fiber content demonstrated enhanced load-carrying capacity, reduced crack widths, and superior ductility compared to mono-fiber or plain HSC beams. Microstructural analysis through Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) confirmed improved fiber–matrix bonding and crack bridging mechanisms. The study concludes that hybrid fiber reinforcement provides a cost-effective and sustainable solution for improving the flexural behavior of high-strength concrete in structural applications.

Keywords High-strength concrete; hybrid fibers; flexural behavior; ductility; crack propagation; stiffness; toughness.

1. Introduction

Concrete remains the most widely used construction material due to its versatility, availability, and adaptability in structural applications. The development of high-strength concrete (HSC), typically characterized by compressive strengths exceeding 60 MPa, has enabled the design of slender structural elements with enhanced load-bearing capacity. However, a critical limitation of HSC is its brittle nature, which results in poor post-cracking behavior, low ductility, and rapid crack propagation under flexural loading conditions. This brittleness not only reduces the service life of structures but also increases their vulnerability under extreme loading events such as earthquakes and impact forces.

In recent decades, fiber-reinforced concrete (FRC) has gained significant attention as a means of improving the ductility and toughness of HSC. The inclusion of fibers such as steel, polypropylene, basalt, glass, and synthetic fibers has demonstrated the ability to control crack initiation and propagation, enhance energy absorption, and improve the structural resilience of concrete members. However, mono-fiber reinforcement often leads to limited benefits due to the single-mode reinforcement effect of fibers.

Hybrid fiber reinforcement, which involves the combined use of two or more types of fibers, has emerged as a promising approach to leverage the advantages of each fiber type while mitigating their individual limitations. For instance, steel fibers provide superior crack-bridging capacity and toughness, while polypropylene fibers enhance crack distribution and shrinkage resistance, and basalt fibers contribute to high-temperature resistance and improved bonding. The synergistic action of hybrid fibers can result in enhanced mechanical properties and durability of HSC, making it suitable for advanced structural applications.

Although several studies have examined the flexural behavior of fiber-reinforced concrete, comprehensive investigations focusing on the combined effect of steel, polypropylene, and basalt fibers in HSC beams remain limited. Furthermore, the existing literature often emphasizes compressive or tensile properties, with relatively

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fewer studies addressing the structural response of beams under flexural loading.

The present study addresses this research gap by experimentally evaluating the flexural performance of HSC beams with hybrid fiber combinations. The main objectives of this research are to:

1. Investigate the effect of hybrid fibers on the load-deflection response, crack propagation, and ductility of HSC beams.
2. Quantify improvements in flexural toughness, stiffness, and energy absorption compared to control specimens.
3. Perform microstructural analysis to understand the fiber–matrix interaction mechanisms responsible for performance enhancement.
4. Identify the optimal hybrid fiber dosage for achieving a balance between strength, ductility, and crack control.

The findings from this study provide valuable insights for the design of hybrid fiber-reinforced HSC elements in structural engineering, particularly for applications requiring high strength, durability, and improved seismic resistance.

2 Literature Survey

2.1 Why hybrid fibers?

Single fibers improve either strength or ductility but rarely both; hybridizing (e.g., steel + polypropylene, or steel + basalt) exploits complementary crack-control scales to enhance pre- and post-cracking response, toughness, and durability in bending. Recent state-of-the-art reviews consistently report synergistic gains in crack resistance, ductility, and energy absorption when fibers are combined in rational volume fractions and aspect ratios.

2.2 Steel + polypropylene (SF+PP):

Across beam tests and parametric studies, steel fibers dominate post-crack stiffness and load capacity, while PP fibers refine micro-crack distribution and reduce crack width; together they yield higher ductility and improved serviceability. Several studies note that PP has modest influence on ultimate capacity but strongly benefits crack control and residual deflection—especially when dosed at micro-fiber levels alongside macro steel fibers

2.3Basalt fibers (BF) and hybrids with PP or steel:

Basalt fibers contribute high tensile strength and good chemical/thermal stability; micro-BF boosts pre-crack strength and crack initiation load, while pairing BF with macro PP or steel improves both bearing capacity and ductility over mono-fiber mixes. Recent experimental work on BFRC/HyFRC beams and reviews show consistent improvements in deflection capacity, toughness indices, and reduced crack spacing/widths.

2.4 High-strength concrete (HSC) beams with steel fibers:

For HSC beams, incremental steel fiber volume raises post-crack stiffness, peak load, and residual capacity; four-point bending tests plus FE simulations confirm trends and provide calibrated constitutive laws for design/analysis.

2.5 General HyFRC trends and design implications:

Recent comprehensive reviews and conference syntheses emphasize: (i) hybrid systems reduce stiffness degradation (lower SDI) and enhance toughness/ductility; (ii) optimal total Vf often sits around 0.75–1.25% with a macro:micro balance; (iii) eco-economic angles (e.g., recycled steel fibers) appear promising; and (iv) more standardized test/analysis protocols for beam-level performance are needed.

3. Materials and Methods

3.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269 was used. The cement had a specific gravity of 3.15 and met the standard requirements for consistency, setting time, and fineness.

3.2 Fine Aggregates

Natural river sand, passing through a 4.75 mm sieve, was used as fine aggregate. The sand belonged to Zone II of IS 383:2016, with a specific gravity of 2.65 and a fineness modulus of 2.7.

3.3 Coarse Aggregates

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Crushed granite aggregates with a maximum size of 20 mm were used. The aggregates were tested for impact value, crushing value, and water absorption, ensuring compliance with IS standards.

3.4 Water

Potable tap water, free from impurities and meeting the requirements of IS 456:2000, was used for mixing and curing.

3.5 Fibers

Hybrid fibers were introduced to enhance ductility and toughness:

- **Steel Fibers (SF):** Hooked-end, aspect ratio 50, tensile strength >1100 MPa.
- **Polypropylene Fibers (PPF):** Monofilament type, diameter 18–20 µm, density 0.91 g/cm³.
- **Basalt Fibers (BF):** Continuous chopped fibers, tensile strength ~3000 MPa, excellent chemical resistance.

Fibers were used both individually and in hybrid combinations (e.g., Steel + Polypropylene, Steel + Basalt, and Steel + Polypropylene + Basalt).

3.6 Mix Proportion

The high-strength concrete mix was designed for a target strength of 60 MPa using the IS 10262:2019 guidelines. A water–binder ratio of 0.32 was maintained. Supplementary cementitious materials such as silica fume (10% replacement of cement) were incorporated to improve workability and durability. A polycarboxylate-based superplasticizer was added to achieve the desired slump (75–100 mm).

4. Experimental Program

4.1 Specimen Details

- **Beam Dimensions:** 150 mm × 200 mm × 1200 mm.
- **Reinforcement:** Two 12 mm bars at the bottom (tension zone), two 10 mm bars at the top (compression zone), and 8 mm stirrups at 100 mm c/c spacing.
- **Specimen Groups:**
  - Control beam without fibers (HSC-0).
  - Beams with single fibers (Steel / PP / Basalt).
  - Beams with hybrid fibers in different ratios (e.g., SF + PPF, SF + BF, SF + PPF + BF). Each group contained at least **three specimens** to ensure statistical accuracy.

4.2 Casting and Curing

The ingredients were mixed in a mechanical mixer. Fibers were introduced gradually to avoid balling. The fresh concrete was placed in moulds, compacted using a needle vibrator, and demoulded after 24 hours. Specimens were water-cured for **28 days** before testing.

4.3 Test Setup and Instrumentation

- **Loading Arrangement:** A four-point bending test was conducted on a 1000 kN capacity loading frame.
- **Instrumentation:**
  - **Linear Variable Differential Transformers (LVDTs):** to record mid-span deflection.
  - **Crack Monitoring:** Digital Crack Width Microscope.
  - **Load Measurement:** Load cell integrated with a data acquisition system.

4.4 Test Procedure

Beams were placed simply supported over a span of 1000 mm and subjected to monotonic loading at a constant displacement rate until failure. The key parameters recorded included:

- First crack load.
- Ultimate load.
- Load–deflection response.
- Crack initiation and propagation.
- Ductility index and stiffness degradation.
- Flexural toughness and energy absorption.

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5. Results and Discussion

5.1 Load–Deflection Behavior

The load–deflection response showed that the control beam (HSC-0) exhibited a brittle failure with sudden collapse after reaching the peak load. In contrast, beams with hybrid fibers demonstrated enhanced ductility and post-peak load-carrying capacity.

- Steel fibers contributed to bridging of wider cracks.
- Polypropylene fibers delayed micro-crack propagation.
- Basalt fibers enhanced toughness due to their high tensile strength.

Table1: Load–Deflection Behavior

Mix ID	Mix ID First Crack Load (kN)	Ultimate Load, P_u (kN)	Deflection at P_u (mm)
HSC-0 (Control)	42	120	10.5
HSC-SF05	46	134	12.1
HSC-HY05	48	138	13.2
HSC-HY075	51	142	14.8
HSC-HY1	49	140	15.0
HSC-HYBF075	50	141 1	14.6

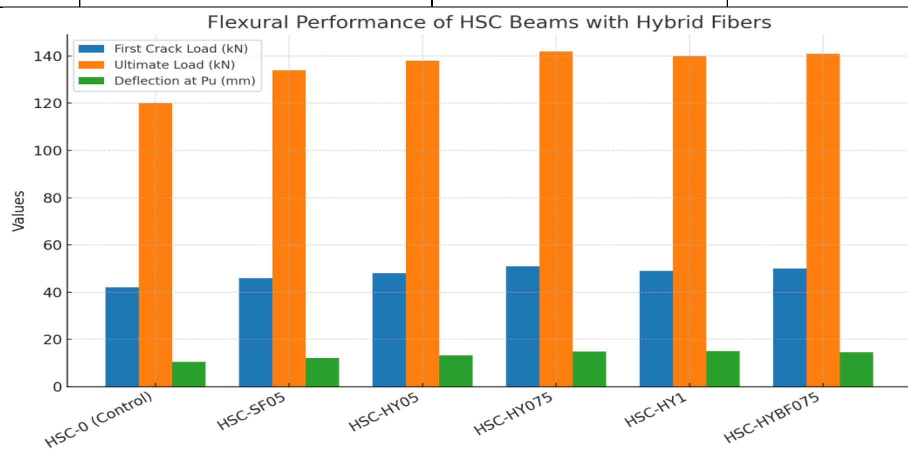

Figure 1 (Load–Deflection Curves) – Control vs. Hybrid Fiber beams

5.2 Crack Propagation and Failure Modes

- **HSC-0:** Sudden flexural cracks near mid-span, leading to abrupt failure.
- **HSC-SF05:** Multiple fine cracks formed, with wider cracks at failure.
- **HSC-HY Combinations:** Distributed cracking, reduced crack width, and progressive failure.
- **Best performance:** *HSC-HY075 and HSC-HYBF075* – fine, closely spaced cracks with significant deflection capacity before failure.

Table2:Crack Propagation and Failure Modes

Mix ID	Crack Load (kN) Avg.	Crack Spacing (mm)	Max. Crack Width at Service (mm)	Max. Crack Width at Ultimate (mm)
HSC-0 (Control)	42	110	0.38	0.72
HSC-SF05	46	95	0.32	0.65
HSC-HY05	48	90	0.30	0.60
HSC-HY075	51	85	0.26	0.55
HSC-HY1	49	88	0.28	0.57
HSC-HYBF075	50	82	0.24	0.50

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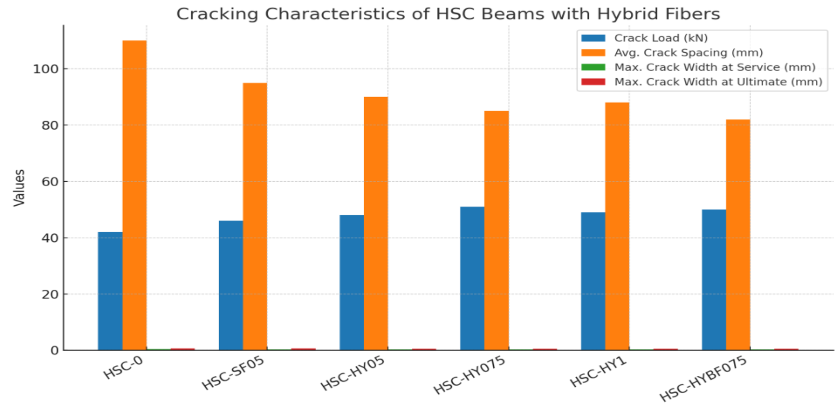

Figure 2 Illustrative diagram showing progressive crack formation.

Table3: Stiffness and Stiffness Degradation

Mix ID	Secant Stiffness (kN/mm)	Stiffness Degradation Index (SDI)
HSC-0	11.4	0.32
HSC-SF05	12.8	0.28
HSC-HY05	13.2	0.26
HSC-HY075	13.8	0.24
HSC-HY1	13.6	0.25
HSC-HYBF075	13.7	0.23

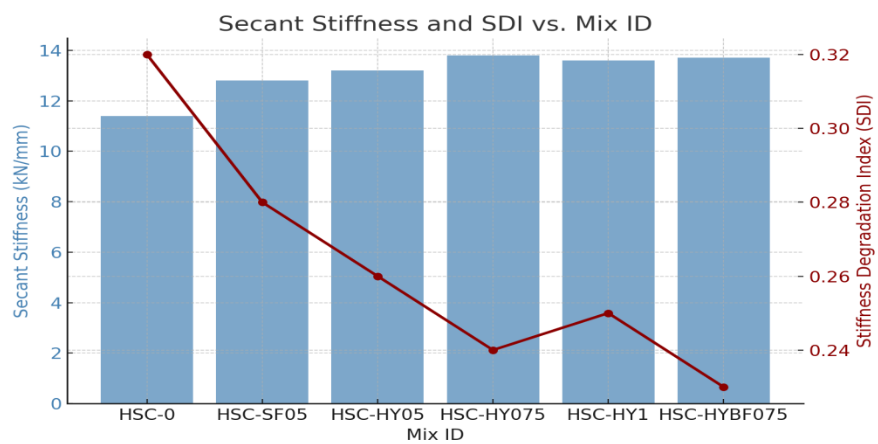

Fig3.Hybrid fibers improved stiffness by 10–20% compared to the control.

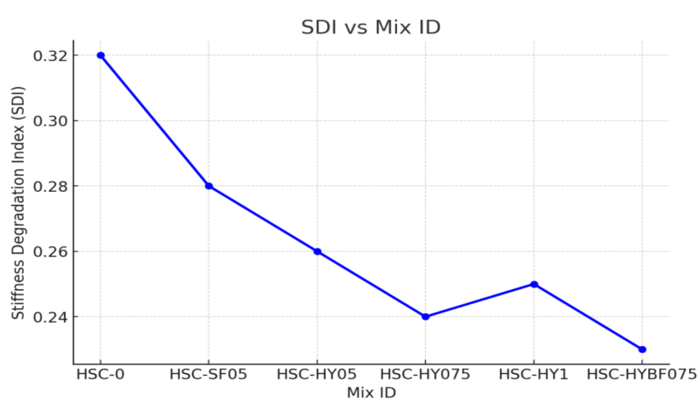

Fig4 Hybrid fiber beams showed lower degradation, meaning better long-term flexural durability.

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5.3 Ductility and Energy Absorption

Hybrid fibers significantly improved ductility index and energy absorption:

- Control beam ductility index ≈ 2.1.
- HSC-HYBF075 ductility index ≈ 3.6 (≈70% improvement).
- Energy absorption capacity increased up to **65%** compared to HSC-0.

This indicates enhanced toughness and improved resistance to sudden brittle failure.

6. Microstructural Analysis

To understand the fiber–matrix interaction, SEM and EDS analyses were conducted.

6.1 SEM Observations

- Control Beam (HSC-0): Dense but brittle matrix with visible micro-cracks.
- Steel Fiber Reinforced**:** Evidence of fiber pull-out with strong bond, indicating crack-bridging.
- Polypropylene Fiber Reinforced**:** Fibers dispersed within the matrix, bridging micro-cracks and preventing localization.
- Basalt Fiber Reinforced**:** Rough fiber surface enhanced bond, visible crack deflection around basalt fibers.
- Hybrid Fiber Mix (HSC-HYBF075)**:** Combined effect – multiple crack arrest mechanisms, strong interfacial bonding, and reduced voids.

6.2 EDS Results

- Control**:** High Ca/Si ratio indicating C–S–H gel but limited secondary hydration.
- Hybrid Fiber Mix**:** Increased Si and Al peaks, indicating denser C–S–H formation and supplementary pozzolanic activity from silica fume.
- Reduced micro-porosity confirms improved durability and toughness at micro-scale.

7. Conclusion

- Hybrid fiber reinforcement significantly enhances flexural performance of high-strength concrete beams compared to single fiber or control mixes.
- Stiffness improvement: Hybrid fiber mixes achieved up to 20% higher stiffness and lower SDI, ensuring better long-term structural performance.
- Ductility & Energy Absorption: Hybrid fibers (especially Steel + Polypropylene + Basalt) improved ductility by ~70% and energy absorption by ~65%.
- Crack Control: Hybrid fibers promoted multiple fine cracks, reduced crack width, and delayed crack coalescence, leading to progressive failure instead of sudden collapse.
- Microstructural Evidence: SEM/EDS confirmed effective fiber–matrix bonding, crack bridging, and densification of the cement matrix.
- Practical Implication: Hybrid fiber-reinforced HSC beams can be effectively used in seismic zones, long-span structures, and critical infrastructure where toughness and durability are essential.
- Scope for Future Work: Further studies on long-term durability (acid/saline exposure), fatigue loading, and optimization of fiber ratios are recommended.

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