Experimental Evaluation Of Flexural Response In Steel Fiber Enhanced High Performance Concrete Beams

Swapneel Satone[1], Dr. K.V. Boobala Krishnan[2], Dr. M . Palanisamy[3], K. Jeevanandan[4] Dr. Prasoon P P[5], Y.Dasthagir[6]

[1]Professor & Head, Department of Civil Engineering, K.D.K. College of Engineering, Nagpur-440024, India, ssatone1980@yahoo.com.

[3]Assistant Professor (SS), Department of Civil Engineering ,Dr. N.G.P.Institute of Technology, Tamil nadu ,India, boobalakrishnan007@gmail.com.

[3]Professor & Head , Department of Civil Engineering ,Balaji Institute of Technology and Science, Narsampet, Warangal ,Telangana ,India, mpalanisamym@gmail.com.

[4]Assistant Professor, Department of Civil Engineering, Dhanalakshmi Srinivasan College Of Engineering ,Coimbatore,Tamil nadu ,India,jeevanandankanagavel@gmail.com.

[5]Assistant Professor, Department of Civil Engineering ,College Of Engineering Kidangoor Kidangoor South P.O, Kottayam – 686 583,Kerala,India, prasoonkollam@gmail.com.

[6]Assistant Professor, Department of Civil Engineering ,KSRM College Of Engineering Autonomous,Kadapa,Andhra Pradesh.India. dasthagir.y@gmail.com.

Abstract

This research presents an experimental investigation into the flexural behavior of High Performance Concrete (HPC) beams incorporating varying volumes of hooked-end steel fibers. While HPC exhibits excellent compressive strength and durability, its brittleness under flexural loading is a key limitation. To address this, steel fibers were introduced at volume fractions of 0%, 0.5%, 1.0%, and 1.5%, and twelve beam specimens were tested under four-point bending following ASTM C1609/C1609M standards. The study evaluated critical parameters including first crack load, ultimate load, loaddeflection characteristics, crack propagation, and failure mode.Results indicate that the inclusion of steel fibers significantly enhances flexural strength, ductility, and energy absorption capacity. Beams with 1.5% fiber content showed a 45% increase in peak load and a threefold increase in ultimate deflection compared to control specimens. Crack control

1 . INTRODUCTION

High Performance Concrete (HPC) offers superior strength and durability compared to conventional concrete, making it suitable for modern infrastructure. However, HPC remains brittle and susceptible to sudden failure under flexural loads. To address this, steel fibers are incorporated into the mix to improve ductility and toughness. Steel Fiber Reinforced Concrete (SFRC) combines the advantages of high strength and improved post-cracking behavior, which is essential for applications like beams, slabs, and pavements. This paper presents an experimental evaluation of the flexural response of steel fiber reinforced HPC beams, focusing on crack development, load-deflection characteristics, and ductility enhancement.

2 . MATERIALS AND METHODS

This study involved the design and evaluation of High Performance Concrete (HPC) beams reinforced with steel fibers. The experimental program was carefully structured to investigate the influence of varying fiber contents on the flexural behavior of concrete beams.

3 .1 Materials

also improved, with multiple fine cracks forming instead of a single wide crack. The mode of failure changed from brittle to ductile with increasing fiber dosage. These findings demonstrate the effectiveness of steel fibers in transforming HPC into a more resilient and flexure-tolerant material, making it suitable for critical structural applications such as earthquakeresistant buildings, bridge decks, and precast elements.

Keywords: *High Performance Concrete (HPC),Steel Fiber Reinforced Concrete (SFRC),Flexural Strength, LoadDeflection Behavior, Crack Propagation, Ductility.*

2.1.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS: 12269-2013 was used as the primary binder. This grade is known for its high early strength, which is essential for High Performance Concrete applications. The cement was tested for specific gravity (3.15), standard consistency (29%), initial and final setting times, and compressive strength to confirm its suitability.

2.1.2 Silica Fume

Silica fume, a by-product of the silicon and ferrosilicon alloy industry, was used to partially replace cement (10% by weight). It is highly pozzolanic and helps improve the microstructure of concrete by refining the pore structure, increasing compressive strength, and reducing permeability. The specific surface area of the silica fume used was around 20,000 m^2/kg.

2.1.3 Fine Aggregate

Locally available clean river sand conforming to Zone II grading as per IS: 383-2016 was used. The sand was washed and sieved to remove silt and clay. Its fineness modulus was found to be 2.65, and it had a specific gravity of 2.63. Proper grading and cleanliness of fine aggregate are essential for achieving high workability and compactness in HPC.

2.1.4 Coarse Aggregate

Crushed granite of nominal maximum size 12 mm was used as coarse aggregate. It had a specific gravity of 2.70 and was free from dust and impurities. The aggregates were angular in shape, aiding mechanical interlocking and improving strength. Water absorption was limited to 0.5%, which is desirable for high strength mixes.

2.1.5 Water

Clean potable water was used for both mixing and curing of concrete. The water used met the requirements of IS: 456-2000, with no harmful substances like chlorides or sulfates that could affect hydration or durability.

2.1.6 Superplasticizer

A high-range water-reducing admixture (HRWRA) based on polycarboxylate ether (PCE) was employed to enhance workability without increasing the water-cement ratio. This helped maintain the low w/c ratio (~0.32) required for high performance concrete. The dosage was kept at 2% of the binder content, based on preliminary trials for slump flow and retention.

2.1.7 Steel Fibers

Hooked-end steel fibers with a length of 30 mm and a diameter of 0.5 mm were used, yielding an aspect ratio of 60. The tensile strength of the fibers was above 1100 MPa. These fibers were added at 0%, 0.5%, 1.0%, and 1.5% volume fractions (Vf) to enhance the ductility, toughness, and post-cracking resistance of the HPC. Proper dispersion of fibers was ensured during mixing to prevent balling.

2.2 Mix Design and Proportions

The concrete mix was designed to achieve a compressive strength exceeding 60 MPa after 28 days. Silica fume was added as a partial cement replacement, while the water-cement ratio was limited to 0.32 to maintain high strength and low permeability. Table 1 provides the detailed mix proportions: **Table 1. HPC Mix Proportions (per m³ of concrete)**

Material	**Quantity (kg/m³)**
Cement (OPC 53)	400
Silica Fume	40
Fine Aggregate	650
Coarse Aggregate	1150
Water	150
Superplasticizer	8 (2% of binder)
Steel Fibers (Vf)	0 / 39 / 78 / 117

2.3 Specimen Details and Curing

A total of twelve reinforced concrete beam specimens were cast in the laboratory. The beam dimensions were 150 mm × 150 mm × 1000 mm. Four groups were prepared based on fiber content: 0% (control), 0.5%, 1.0%, and 1.5%. Each group had three identical specimens to ensure repeatability.

The fresh concrete was placed in molds in two layers, each compacted using a table vibrator. After 24 hours, specimens were demolded and cured in clean water at 27±2°C for 28 days to ensure proper hydration and strength development. **2.4 Testing Procedure**

Flexural testing was conducted using a **four-point bending test** setup in accordance with **ASTM C1609/C1609M-19** standards. The beams were tested under a displacement-controlled mode using a universal testing machine (UTM) with a loading rate of 0.1 mm/min. The load and mid-span deflection were recorded continuously.

Key parameters observed included:

- First cracking load
- Ultimate load
- Load-deflection behavior
- Crack propagation
- Mode of failure

Crack widths were also visually monitored during loading to assess the fiber bridging effect.

3. Experimental Program

3.1. Specimen Preparation

In this experimental study, a total of **twelve reinforced concrete beam specimens** were prepared and tested. The specimens were designed to investigate the effect of steel fiber volume on the flexural response of High Performance Concrete (HPC). Four groups were considered based on fiber volume fractions: **0% (control)**, **0.5%**, **1.0%**, and **1.5%**, with **three beams per group** to ensure result reliability and repeatability.

Each beam specimen was cast in a standard rectangular mold with dimensions of **150 mm × 150 mm × 1000 mm**. The concrete was mixed in a pan-type mixer, where dry ingredients (cement, silica fume, fine and coarse aggregates) were first mixed thoroughly. Steel fibers were then added gradually to ensure uniform distribution throughout the mix. Finally, water and superplasticizer were introduced to achieve the desired workability. After placing the concrete into molds in two layers, each layer was compacted using a table vibrator to eliminate air voids. The surface was finished with a trowel, and the specimens were covered with moist gunny bags for 24 hours. After demolding, the beams were transferred to a curing tank and cured under water at **27 ± 2°C** for **28 days** to ensure proper hydration and strength development.

3.2. Testing Setup

After 28 days of curing, the beam specimens were subjected to a **four-point bending test** to evaluate their flexural performance. The test was conducted using a **Universal Testing Machine (UTM)** with a loading capacity of 1000 kN. The setup was designed in accordance with the guidelines of **ASTM C1609/C1609M**, which is the standard test method for evaluating the flexural performance of fiber-reinforced concrete. In the four-point loading configuration, the specimen was simply supported on two rollers, and two equally spaced point loads were applied symmetrically at one-third span distances from the supports. This configuration ensures a **constant moment region** between the load points and helps in observing the pure flexural behavior of the concrete beam.

A **displacement-controlled loading rate of 0.1 mm/min** was applied to capture both the pre-crack and postcrack behavior with high accuracy. A Linear Variable Differential Transformer (LVDT) was used to measure **mid-span deflection**, and the applied load was recorded through a load cell integrated with the testing machine. Throughout the test, visual observations were made to identify the **crack initiation point**, **crack width development**, and **final mode of failure**. Photographic documentation was done to record crack patterns.

The following parameters were measured and analyzed for each specimen:

- **First cracking load** • **Ultimate load capacity** • **Load-deflection behavior** • **Crack width and propagation** • **Failure mode (brittle or ductile)**

This testing methodology allowed for a comprehensive assessment of how varying steel fiber contents influenced the structural behavior and flexural performance of the HPC beams. **4. Results and Discussion**
The experimental results demonstrate the effect of increasing steel fiber volume on the flexural performance of high performance concrete beams. The data are analyzed in terms of **flexural strength**, **load-deflection behavior**, **crack pattern**, and **energy absorption capacity**.

4.1 Load vs. Deflection Behavior

The addition of steel fibers significantly enhanced both the **peak load** and the **deflection capacity** of the beams. Control specimens failed suddenly after first crack, while fiber-reinforced beams showed improved ductility and energy dissipation.

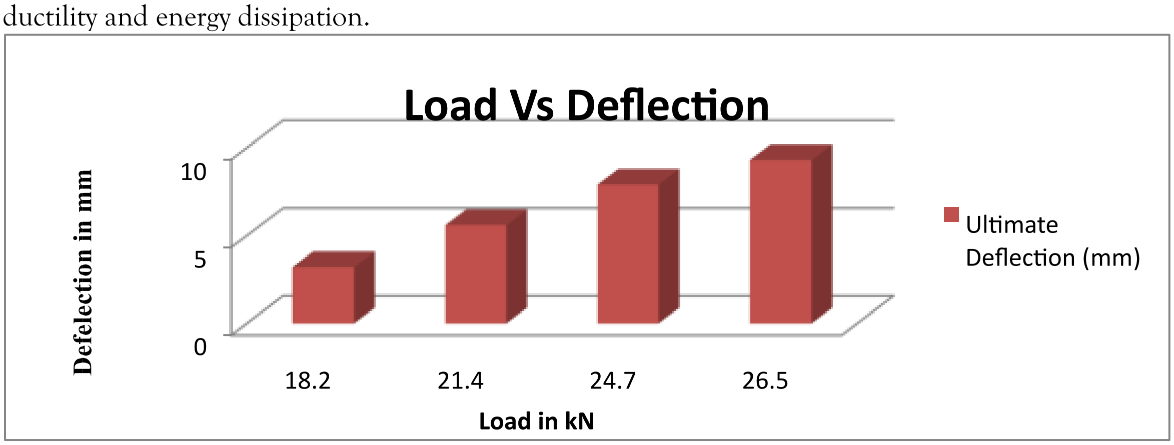

Fig1: Load vs. Deflection behavior

4.2 Flexural Strength and Ductility

Table2. Flexural Strength and Ductility

Fiber Volume (%)	Peak Load (kN)	Ultimate Deflection (mm)	Toughness (kN·mm)

0.0 (Control) 1.0	18.2	3.2	28.5
0.5	21.4	5.6	52.7
1.0	24.7	7.9	86.3
1.5	26.5	9.3	105.8

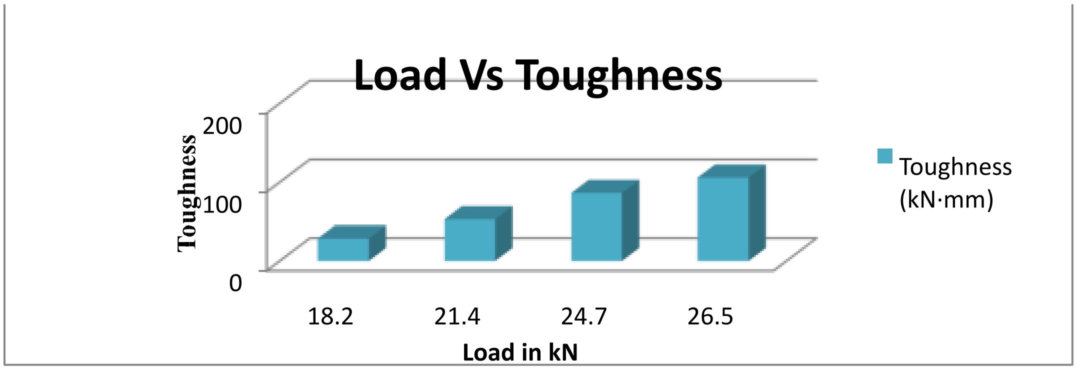

Fig1: Load vs Toughness behavior

- **Flexural strength** increased by up to **45%** with 1.5% steel fibers.
- **Ductility (ultimate deflection)** almost **tripled** from 3.2 mm to 9.3 mm.
- **Toughness** (area under the curve) also improved, indicating better energy absorption.

4.3 Crack Pattern and Failure Mode

- **Control Beams (0% Fiber)**: Single, wide cracks appeared suddenly after peak load, leading to brittle failure.
- **SFRC Beams**: Multiple fine cracks developed gradually. The presence of steel fibers delayed crack propagation and enhanced post-cracking strength.
- **1.5% Fiber Beams** showed the most ductile behavior with tight crack spacing and significant residual strength after peak load.

4.4 Discussion

The improved performance is attributed to the **bridging effect** of steel fibers, which enhances **tensile capacity after cracking**. As fiber content increased:

- Cracks became finer and more distributed.
- The concrete exhibited **strain-hardening behavior**.
- The energy required to fail the beam increased, showing better resistance to dynamic and seismic loads.

However, at fiber volumes beyond 1.5%, workability issues may arise, which can affect uniform distribution and structural integrity.

5. CONCLUSIONS

Based on the experimental investigation of steel fiber-reinforced high performance concrete (HPC) beams under flexural loading, the following conclusions were drawn:

1. **Flexural Strength Improvement**: The addition of steel fibers significantly improved the flexural capacity of HPC beams. Beams with 1.5% steel fiber content exhibited an increase in ultimate load by approximately **45%** compared to the control specimen.
2. **Enhanced Ductility and Toughness**: Steel fibers effectively enhanced the ductility and energy absorption capacity of the beams. The load-deflection behavior transitioned from brittle to ductile with increasing fiber volume, especially in the 1.0% and 1.5% fiber content beams.

3. **Crack Control**: Fiber inclusion led to multiple micro-cracks instead of a single major crack, resulting in improved **crack width control** and more stable post-cracking behavior. This is particularly beneficial in structures exposed to dynamic or seismic loading.
4. **Optimal Fiber Content**: A steel fiber volume fraction of **1.0% to 1.5%** was found to be optimal for balancing strength gains and workability. Beyond 1.5%, the mix may suffer from reduced workability and fiber balling.
5. **Failure Mode Transition**: The mode of failure changed from a **sudden brittle fracture** in the control beams to a **progressive ductile failure** in fiber-reinforced beams, demonstrating better performance under service and ultimate loads.

6. REFERENCES

1. ACI Committee 544 (2018). Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete. ACI 544.3R18, American Concrete Institute, Farmington Hills, MI, USA.
2. ASTM C1609/C1609M-19. Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading). ASTM International, West Conshohocken, PA.
3. IS 516:2018. Methods of Tests for Strength of Concrete. Bureau of Indian Standards, New Delhi.
4. IS 456:2000. Plain and Reinforced Concrete – Code of Practice. Bureau of Indian Standards, New Delhi.
5. Naaman, A.E. (2007). High Performance Fiber Reinforced Cement Composites. Techno Press, USA.
6. Li, V.C. (2003). "On Engineered Cementitious Composites (ECC): A Review of the Material and Its Applications." Journal of Advanced Concrete Technology, 1(3), 215–230.
7. Nataraja, M.C., Dhang, N., & Gupta, A.P. (1999). "Stress–strain curves for steel-fiber reinforced concrete under compression." Cement and Concrete Composites, 21(5–6), 383–390.
8. Banthia, N., & Trottier, J.F. (1995). "Concrete reinforced with deformed steel fibers, Part I: Bond-slip mechanisms." ACI Materials Journal, 92(5), 435–446.
9. Soroushian, P., & Lee, C.D. (1990). "Flexural Strength of Steel Fiber Reinforced Concrete Beams." ACI Structural Journal, 87(1), 44–47.
10. Shah, S.P., & Rangan, B.V. (1971). "Fiber Reinforced Concrete Properties." ACI Journal Proceedings, 68(2), 126–135.
11. Rasheed, H.A., & Mo, Y.L. (2002). "Effect of Steel Fibers on the Strength and Ductility of Reinforced Concrete Beams." Materials and Structures, 35, 396–404.
12. Armelin, H.S., & Banthia, N. (1998). "Predicting the flexural toughness of steel fiber reinforced concrete from the properties of fiber-matrix bond." Cement and Concrete Composites, 20(5), 269–276.
13. Yoo, D.Y., & Banthia, N. (2016). "Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review." Cement and Concrete Composites, 73, 267–280.
14. Parra-Montesinos, G.J. (2006). "Shear Strength of Beams with Deformed Steel Fibers." ACI Structural Journal, 103(2), 244–251. 15. Bencardino, F., Rizzuti, L., Spadea, G., & Swamy, R.N. (2010). "Stress-strain behavior of steel fiber-reinforced concrete under compression." Cement and Concrete Composites, 32(9), 716–726.