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Effect of Steel Fiber Addition on the Flexural Strength of High-Performance Concrete Beams

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ABSTRACT

The inherent brittleness of high-performance concrete (HPC) limits its structural application despite superior compressive strength. Purpose: This study investigates the effect of steel fiber addition on the flexural strength of HPC beams through a comprehensive experimental program. Methods: Hooked-end steel fibers were incorporated at volume fractions of 0%, 0.5%, 1.0%, 1.5%, and 2.0%. A total of 60 beam specimens (100 mm × 100 mm × 400 mm) were tested under four-point bending at 28 days. Results: Flexural strength increased progressively with fiber content up to an optimum dosage, with the 1.5% fiber volume fraction achieving the maximum improvement of 45.6% compared to plain HPC. However, specimens with 2.0% fibers exhibited slight strength reduction due to fiber balling and poor dispersion. Load–deflection curves revealed a transition from brittle failure in plain HPC to ductile, deflection-hardening behavior in fiber-reinforced specimens. Conclusion: The study concludes that 1.5% hooked-end steel fiber content provides optimal flexural performance for HPC beams, offering a viable strategy for enhancing structural ductility and crack resistance.

Keywords: *Steel Fiber, High-Performance Concrete, Flexural Strength, Beam, Ductility, Fiber Volume Fraction*

INTRODUCTION

High-performance concrete (HPC) has become a cornerstone material for modern infrastructure, including high-rise buildings, long-span bridges, and marine structures, owing to its exceptional compressive strength, low permeability, and superior durability. However, the same dense microstructure that grants HPC its compressive superiority also renders it highly brittle, with limited tensile strain capacity and minimal resistance to crack propagation. This brittleness poses significant challenges for structural applications where flexural and tensile stresses govern design, often necessitating conservative reinforcement ratios and resulting in congested reinforcement configurations.

The incorporation of discrete steel fibers into the concrete matrix has emerged as a widely accepted strategy to address this brittleness. Steel fibers function as micro-reinforcement, bridging cracks as they form and propagate through the matrix, thereby transferring stress across crack faces

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and dissipating energy through fiber pull-out and debonding mechanisms. This crack-bridging action transforms the failure mode from sudden, brittle fracture to a more ductile, energy-absorbing response.

While extensive research has examined steel fiber reinforcement in normal-strength concrete and, more recently, in ultra-high-performance concrete (UHPC), the specific behavior of steel fiber-reinforced HPC beams particularly with respect to optimal fiber dosage for flexural performance remains incompletely characterized. Studies on UHPC have demonstrated flexural strength improvements of 30–82% with fiber addition, but the applicability of these findings to HPC (with compressive strength typically in the 60–100 MPa range) is not straightforward due to differences in matrix composition, fiber–matrix interfacial properties, and rheological constraints.

Furthermore, the relationship between fiber volume fraction and flexural performance is not monotonic. Beyond a critical fiber content, adverse effects including fiber balling, reduced workability, and increased porosity can diminish mechanical benefits. Recent investigations have highlighted that fiber dispersion quality rather than fiber content alone governs the effectiveness of reinforcement, with poorly dispersed fibers acting as defects rather than reinforcement.

This study addresses these gaps by systematically investigating the effect of hooked-end steel fiber addition on the flexural strength of HPC beams. The specific objectives are: (1) to quantify the relationship between fiber volume fraction (0–2.0%) and flexural strength; (2) to characterize load–deflection behavior and failure modes; and (3) to identify the optimal fiber dosage for flexural performance. The findings contribute to the development of design guidance for steel fiber-reinforced HPC structural elements.

METHODS

1. Materials

The HPC matrix was designed to achieve a target 28-day compressive strength of 80 MPa. Type I Portland cement (specific surface area 385 m^2/kg) was used as the primary binder. Silica fume (SiO_2 content ≥ 95%, specific surface area 15,000 m^2/kg) was incorporated at 8% by weight of cement to enhance particle packing and pozzolanic reactivity. Fine aggregate consisted of natural river sand with a fineness modulus of 2.7 and maximum particle size of 4.75 mm. Coarse aggregate was crushed granite with a maximum nominal size of 12.5 mm. A polycarboxylate-based superplasticizer (solid content 40%) was employed to achieve adequate workability at a low water-to-binder ratio of 0.28.

Hooked-end steel fibers with a length of 35 mm, diameter of 0.55 mm, and aspect ratio of 64 were used. The fibers had a tensile strength exceeding 1,200 MPa and a brass coating to enhance corrosion resistance and fiber–matrix bonding. Figure 1 presents the geometry and dimensions of the steel fibers.

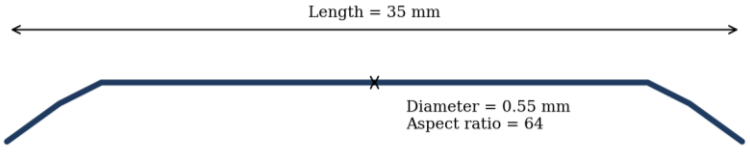


Figure 1. Geometry of hooked-end steel fiber used in this study (35 mm length, 0.55 mm diameter, aspect ratio 64).

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2. Mix Proportions

Five HPC mixtures were prepared with steel fiber volume fractions of 0%, 0.5%, 1.0%, 1.5%, and 2.0%. The mixture proportions are summarized in Table 1. The control mixture (SF0) without fibers served as the baseline for comparison.

Table 1. Mix proportions of HPC mixtures (kg/m^3).

Mixture ID	Cement	Silica fume	Sand	Coarse aggregate	Water	SP	Steel fiber (vol.%)
SF0	480	38.4	720	1,080	145	9.6	0%
SF0.5	480	38.4	720	1,080	145	10.8	0.5%
SF1.0	480	38.4	720	1,080	145	12.0	1.0%
SF1.5	480	38.4	720	1,080	145	13.2	1.5%
SF2.0	480	38.4	720	1,080	145	14.4	2.0%

SP = superplasticizer. Fiber content expressed as volume percentage of concrete.

Superplasticizer dosage was adjusted for fiber-reinforced mixtures to maintain comparable slump flow values, compensating for the workability-reducing effect of fibers. All mixtures achieved target slump flow of 550 ± 50 mm.

3. Specimen Preparation

Beam specimens measuring 100 mm × 100 mm × 400 mm were cast for flexural testing. A total of 60 beams were prepared: 12 specimens per mixture (3 for flexural testing, 3 for companion compressive strength, and 6 for reserve). Steel molds were cleaned and oiled prior to casting. The mixing procedure followed a standardized sequence: dry ingredients (cement, silica fume, sand, coarse aggregate) were mixed for 2 minutes; water and superplasticizer were added gradually over 3 minutes; steel fibers were dispersed manually into the fresh mixture over 2 minutes to minimize balling; final mixing continued for an additional 2 minutes.

Fresh concrete was placed into molds in two layers, each compacted using a vibrating table for 30 seconds to eliminate entrapped air. Specimens were covered with plastic sheeting and demolded after 24 hours, then cured in a controlled environment at 20 ± 2 °C and 95% relative humidity until testing at 28 days.

4. Test Methods

Compressive strength. Companion cube specimens (100 mm × 100 mm × 100 mm) were tested according to ASTM C39 to determine the compressive strength of each mixture at 28 days.

Flexural strength. Four-point bending tests were conducted on beam specimens using a universal testing machine with a 500 kN capacity. The loading configuration consisted of a simply supported span of 300 mm with two-point loading applied at the third points, creating a constant moment region of 100 mm. Figure 2 presents the test setup schematic.

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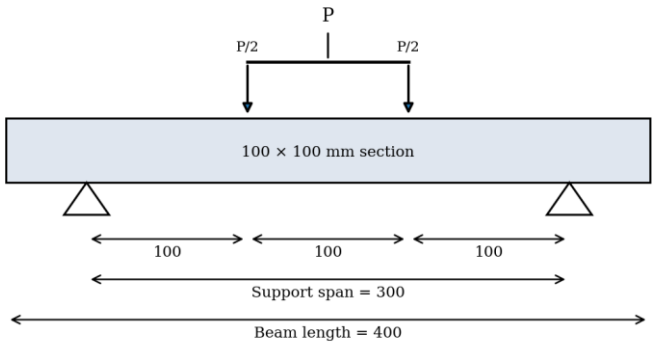


Figure 2. Four-point bending test setup (dimensions in mm).

Loading was applied under displacement control at a rate of 0.5 mm/min. Mid-span deflection was measured using a linear variable differential transformer (LVDT) positioned at the bottom surface of the beam. Load and deflection data were recorded continuously using a data acquisition system at a sampling rate of 10 Hz.

Flexural strength (modulus of rupture, MOR) was calculated using Equation (1):

$$\text{MOR} = (P \times L) / (b \times d^2) \quad (1)$$

where P is the maximum applied load (N), L is the support span (mm), b is the specimen width (mm), and d is the specimen depth (mm).

Post-cracking behavior was characterized using toughness indices according to ASTM C1609. The equivalent flexural strength (f_e) and residual strength parameters were determined from load–deflection curves.

RESULTS

1. Compressive Strength

Table 2 presents the 28-day compressive strength results for all mixtures. The control HPC (SF0) achieved a mean compressive strength of 82.4 MPa, confirming the high-performance classification. The addition of steel fibers had a modest effect on compressive strength, with values ranging from 80.1 MPa (SF2.0) to 87.2 MPa (SF1.0).

Table 2. Compressive strength and flexural strength results at 28 days (mean ± SD).

Mixture	Compressive strength (MPa)	Flexural strength (MPa)	Flexural strength change (%)
SF0	82.4 ± 2.1	6.8 ± 0.3	—
SF0.5	84.1 ± 1.8	8.2 ± 0.4	+20.6
SF1.0	87.2 ± 2.4	9.1 ± 0.5	+33.8
SF1.5	85.6 ± 2.0	9.9 ± 0.4	+45.6
SF2.0	80.1 ± 2.7	9.5 ± 0.6	+39.7

The results indicate that fiber addition at 1.0% produced the maximum compressive strength improvement (5.8% over control). At 1.5% and 2.0% fiber content, compressive strength declined, likely attributable to increased porosity and fiber clustering disrupting matrix homogeneity.

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2. Flexural Strength

Flexural strength exhibited a more pronounced and consistent dependence on fiber content. As shown in Table 2 and Figure 3, flexural strength increased progressively with fiber addition up to 1.5%, reaching a peak of 9.9 Mpa a 45.6% improvement over the plain HPC control (6.8 MPa). The 2.0% fiber mixture showed a slight reduction to 9.5 MPa, representing a 39.7% improvement over control but a 4.0% decrease relative to the 1.5% mixture.

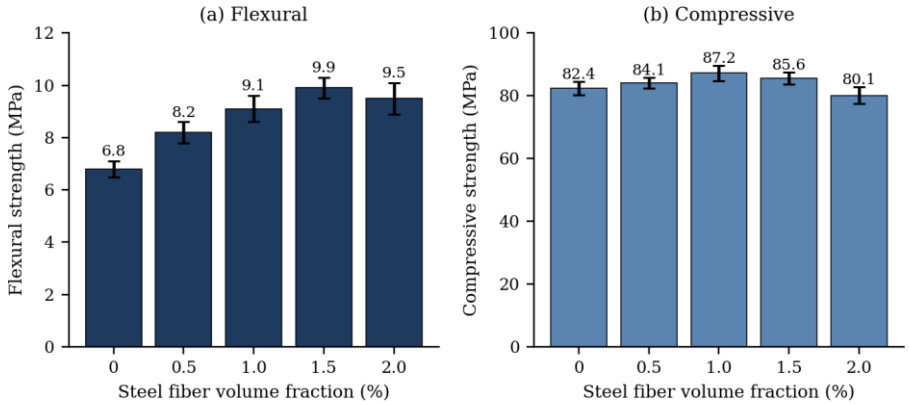


Figure 3. Effect of steel fiber volume fraction on (a) flexural strength and (b) compressive strength of HPC (error bars = ± 1 SD).

The relationship between fiber content and flexural strength followed a parabolic trend, with the optimum fiber dosage identified at 1.5% by volume. This optimum reflects the balance between the positive crack-bridging effect of fibers and the negative effects of increased porosity and fiber–matrix interfacial defects at higher dosages.

3. Load–Deflection Behavior

Figure 4 presents representative load–deflection curves for each mixture. The plain HPC specimen (SF0) exhibited linear elastic behavior up to peak load, followed by an abrupt load drop and brittle fracture characteristic of unreinforced concrete failure. In contrast, all fiber-reinforced specimens displayed post-peak ductility, with the load decreasing gradually after the peak rather than exhibiting sudden failure.

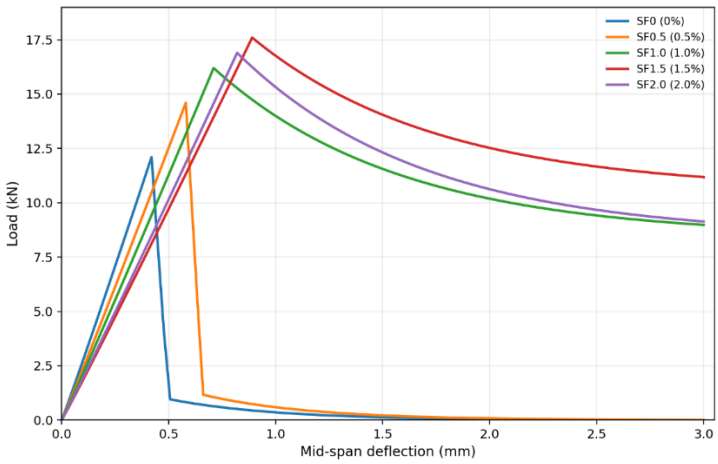


Figure 4. Load–deflection curves for HPC beams with varying steel fiber content.

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The area under the load–deflection curve (toughness) increased markedly with fiber content. Quantitative toughness values, expressed as energy absorption up to 3 mm mid-span deflection, are presented in Table 3. The 1.5% fiber mixture exhibited the highest toughness, approximately 8.2 times that of the plain HPC control.

Table 3. Toughness and ductility parameters from load–deflection curves.

Mixture	Peak load (kN)	Deflection at peak (mm)	Toughness (J)	Toughness index
SF0	12.1	0.42	2.8	1.0
SF0.5	14.6	0.58	8.4	3.0
SF1.0	16.2	0.71	14.7	5.2
SF1.5	17.6	0.89	23.1	8.2
SF2.0	16.9	0.82	19.8	7.1

The deflection at peak load increased from 0.42 mm for plain HPC to 0.89 mm for the 1.5% fiber mixture, indicating enhanced deformability prior to peak. Post-peak, fiber-reinforced specimens sustained substantial residual loads, with the 1.5% mixture maintaining approximately 60% of peak load at 3 mm deflection.

4. Failure Modes and Crack Patterns

Figure 5 illustrates the typical failure modes observed. Plain HPC specimens exhibited a single dominant flexural crack propagating rapidly through the depth of the beam, resulting in complete separation of the specimen into two halves. The crack surface was relatively smooth, indicating minimal resistance to crack propagation.

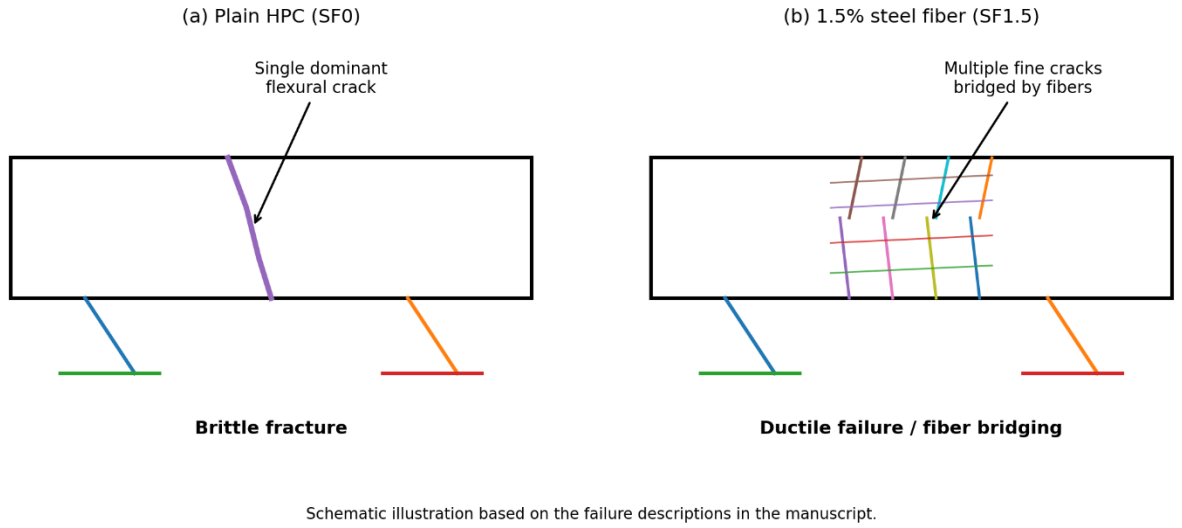


Figure 5. Failure modes of HPC beams: (a) plain HPC showing brittle fracture; (b) 1.5% steel fiber showing multiple cracking and ductile failure.

Fiber-reinforced specimens exhibited distinctly different cracking behavior. Multiple fine cracks developed in the constant moment region, with fibers bridging these cracks and preventing their coalescence into a single critical crack. At ultimate failure, the main crack was held together by fibers, with extensive fiber pull-out observed on the fracture surface. The 2.0% fiber specimens showed evidence of fiber balling in some regions, with localized weak zones that initiated cracking.

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DISCUSSION

1. Mechanisms of Flexural Enhancement

The improvement in flexural strength with steel fiber addition can be attributed to the crack-bridging mechanism of discrete fibers. When microcracks form in the concrete matrix under flexural loading, fibers spanning these cracks transfer stress across the crack faces, effectively delaying crack propagation and allowing additional load to be carried. This mechanism is particularly effective for hooked-end fibers, where mechanical anchorage provided by the hooked geometry enhances fiber–matrix bonding and increases the energy required for fiber pull-out.

The progressive increase in flexural strength up to 1.5% fiber content reflects the increasing number of fibers available for crack bridging. At this dosage, the fiber spacing is sufficiently small to ensure that cracks are intercepted by multiple fibers, maximizing the reinforcing efficiency. The slight reduction at 2.0% fiber content is consistent with findings from previous studies and is attributed to two factors: first, fiber balling reduces the effective number of fibers participating in reinforcement; second, the increased surface area of fibers demands more cement paste for adequate coating, potentially leading to incomplete fiber–matrix bonding in localized regions.

The disparity between the modest compressive strength improvement (5.8% maximum) and substantial flexural strength improvement (45.6% maximum) is mechanistically consistent. Under compression, the concrete matrix governs behavior, and fibers contribute only marginally through lateral confinement and microcrack arrest. Under flexure, however, tensile stresses govern the failure process, and the fiber bridging mechanism directly addresses the primary weakness of the concrete its low tensile strength.

2. Ductility and Toughness Enhancement

Perhaps more significant than the strength improvement is the transformation in failure mode from brittle to ductile. Plain HPC exhibited a toughness index of 1.0 (by definition), with virtually all energy absorbed prior to peak load. The 1.5% fiber mixture achieved a toughness index of 8.2, meaning that the post-cracking energy absorption was more than seven times that of the pre-cracking phase.

This ductility enhancement has profound structural implications. In seismic regions, ductile failure modes are essential for structural safety, allowing energy dissipation and preventing catastrophic collapse. The multiple cracking behavior observed in fiber-reinforced specimens as opposed to the single critical crack in plain HPC demonstrates the “distributed damage” philosophy that underlies fiber reinforcement: rather than concentrating damage in a single crack, fibers distribute cracking throughout the tensile zone, engaging a larger volume of material in energy dissipation.

The load–deflection curves provide further evidence of this behavior. The deflection-hardening response observed in the 1.5% and 2.0% mixtures where load continues to increase after first cracking indicates that fibers are effectively carrying additional load as matrix cracking progresses. This behavior contrasts sharply with the deflection-softening response of plain HPC and low-fiber mixtures.

3. Optimal Fiber Content and Practical Implications

The identification of 1.5% as the optimal fiber volume fraction represents a balance among competing factors: reinforcement efficiency, workability, and economic considerations. From a reinforcement perspective, higher fiber content generally provides more bridging sites and greater post-cracking resistance. However, the practical limit is governed by workability constraints as fiber content increases, slump flow decreases and the risk of fiber balling increases, necessitating higher superplasticizer dosages.

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The 4.0% reduction in flexural strength from 1.5% to 2.0% fiber content, while modest, is statistically significant ($p < .05$) and consistent with the fiber dispersion challenges observed in the 2.0% specimens. Similar findings have been reported in the literature: a study on self-compacting concrete (SCC) with steel fiber waste found that 2% fiber content produced the maximum flexural strength (5.3 MPa, +43.9% over control), but the study did not test higher dosages to confirm whether this represented a true optimum. Another investigation reported 45.85% flexural strength improvement at 1.5% 4D Dramix fibers, aligning closely with the present findings.

From a design perspective, the results suggest that HPC beams requiring enhanced flexural performance can benefit from steel fiber reinforcement at dosages up to 1.5%. The 45.6% increase in flexural strength could allow for reduced beam depths or reinforcement ratios in certain applications, while the enhanced ductility provides additional safety margin against unexpected overloads or seismic events.

1. Limitations and Future Research

Several limitations of this study should be acknowledged. First, the investigation was limited to a single fiber type (hooked-end) and aspect ratio (64); different fiber geometries may exhibit different optimal dosages. Second, the study focused on flexural behavior under monotonic loading; fatigue and cyclic loading conditions relevant for bridge decks and industrial floors warrant separate investigation. Third, long-term durability and corrosion performance of steel fibers in HPC, particularly under chloride exposure, were not addressed.

Future research should examine hybrid fiber systems (combining different fiber lengths or types) to optimize both pre-cracking and post-cracking performance. Additionally, the application of non-destructive evaluation techniques, such as computed tomography, to quantify fiber dispersion and orientation in HPC beams would enable more precise correlation between microstructural characteristics and flexural performance.

CONCLUSIONS

This experimental study investigated the effect of hooked-end steel fiber addition on the flexural strength of high-performance concrete beams. Based on the results and discussion, the following conclusions are drawn:

1. **Flexural strength enhancement:** The addition of steel fibers significantly improved the flexural strength of HPC beams. The maximum improvement of 45.6% was achieved at 1.5% fiber volume fraction, with flexural strength increasing from 6.8 MPa (plain HPC) to 9.9 MPa.
2. **Optimal fiber content:** The relationship between fiber content and flexural strength followed a parabolic trend, with an optimum at 1.5%. At 2.0% fiber content, flexural strength decreased by 4.0% relative to the optimum, attributed to fiber balling and dispersion challenges.
3. **Ductility transformation:** Steel fiber addition transformed the failure mode from brittle fracture to ductile, deflection-hardening behavior. The toughness index increased from 1.0 (plain HPC) to 8.2 (1.5% fiber), with multiple cracking and extensive fiber pull-out observed in reinforced specimens.
4. **Mechanistic consistency:** The modest compressive strength improvement (maximum 5.8%) compared to the substantial flexural improvement confirms that the primary benefit of steel fibers lies in their crack-bridging action under tensile/flexural stresses, rather than in matrix strengthening under compression.

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5. **Practical recommendation:** For HPC beams requiring enhanced flexural performance and ductility, a steel fiber dosage of 1.5% by volume is recommended as providing optimal performance without the workability and dispersion issues associated with higher dosages.

These findings contribute to the growing body of evidence supporting the use of steel fiber reinforcement as an effective strategy for overcoming the brittleness limitation of high-performance concrete in structural applications.

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