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INFLUENCE OF STEEL FIBER VOLUME FRACTION ON THE COMPRESSIVE, TENSILE, AND FLEXURAL STRENGTH OF CONCRETE: A COMPREHENSIVE LITERATURE REVIEW

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Abstract
Steel fiber reinforced concrete (SFRC) has emerged as an innovative engineering material with significant potential to enhance the mechanical performance of conventional concrete. This comprehensive literature review synthesizes peer-reviewed research on the influence of steel fiber volume fraction on the compressive, tensile, and flexural strength of concrete. Through systematic analysis of 25 peer-reviewed studies, this review evaluates how varying steel fiber volume fractions (0% to 3%) affect concrete's primary mechanical properties. The findings demonstrate that compressive strength exhibits non-linear responses with optimal fiber contents typically ranging from 1.0% to 1.5%, while tensile and flexural strengths show more consistent improvements with increasing fiber volume fractions, with gains reaching up to 228% and 180%, respectively. Fiber geometry, aspect ratio, and concrete grade significantly influence mechanical property development. This review identifies critical research gaps and proposes future directions for optimizing SFRC design parameters in structural applications.

1. Introduction

Steel fiber reinforced concrete (SFRC) has gained popularity in the last decades attributed to the improvement of brittleness and low tensile strength of concrete. (L. Zhang *et al.*, 2020) Traditional plain concrete exhibits inherent limitations as a structural material, characterized by high compressive strength but comparatively low tensile strength and poor ductility. These deficiencies restrict concrete applications in scenarios involving tensile stresses, dynamic loading, or situations requiring energy absorption capacity. The brittleness of conventional concrete often results in sudden, catastrophic failure with minimal warning, creating significant safety concerns in critical structural applications.

The introduction of discrete steel fibers into the concrete matrix represents a paradigm shift in composite material engineering. Steel fibers have demonstrated superior crack resistance and improved structural behavior, addressing concrete's limitations of little tensile strength, limited ductileness, and poor crack resistance. (Das *et al.*, 2026) Unlike traditional reinforcement methods that rely on continuous steel bars, steel fibers act as distributed reinforcement throughout the concrete matrix, providing multidirectional crack bridging and enhanced post-cracking behavior.

The mechanical properties of SFRC are fundamentally dependent on several critical parameters, with steel fiber volume fraction being among the most influential. Different types and amounts of steel fibers have varying effects on the improvement of concrete's mechanical properties. Understanding the quantitative relationship between fiber volume fraction and mechanical strength development is essential for optimized SFRC design and rational material selection in engineering practice.

Fiber addition significantly enhances the tensile strength, flexural strength, and ductility of concrete, with variations attributed to the type and volume of fibers used, while the impact on compressive strength was reported as minimal in studies of fiber-reinforced concrete in general. (Salim and Salim, 2024) However, the relationship is not uniformly positive across all mechanical properties or at all fiber concentrations. Research indicates threshold effects and potential diminishing returns or even degradation when fiber volume fractions exceed optimal levels. The compressive strength response differs fundamentally from tensile and flexural responses, exhibiting complex non-linear relationships with fiber content that depend on concrete matrix characteristics and fiber geometry.

The practical significance of SFRC extends across diverse engineering applications. The addition of steel fibers contributes to increased tensile strength and crack resistance, addressing common issues such as reflective cracking and fatigue failure in concrete pavements. (Saiteja and Jayakumari, 2023) Beyond pavement applications, SFRC finds utility in tunnel linings, bridge structures, blast-resistant elements, and other high-performance structural applications where improved ductility and crack control are paramount.

From a research perspective, the investigation of steel fiber volume fraction effects represents an active and evolving field. The fire resistance of SFRC has attracted attention, and numerous investigations regarding the residual properties of SFRC have been conducted, with SFRC exhibiting better residual mechanical properties when exposed to elevated temperatures than plain concrete. (P. Zhang *et al.*, 2020) Beyond conventional mechanical testing, researchers have extended SFRC investigations to encompass durability, thermal resistance, seismic performance, and sustainability considerations.

The objective of this comprehensive literature review is to synthesize current knowledge regarding the quantitative influence of steel fiber volume fraction on three primary mechanical properties: compressive strength, tensile strength, and flexural strength. By integrating findings across multiple peer-reviewed studies employing diverse experimental methodologies, concrete grades, and fiber geometries, this review establishes patterns, identifies optimal design parameters, and clarifies the mechanisms underlying strength development in SFRC systems. Furthermore, this review identifies critical gaps in existing knowledge and proposes directions for future research to advance the state-of-the-art in SFRC technology and application.

2. Methodology

2.1 Literature Search Strategy

This comprehensive literature review employed a systematic search of academic databases focusing on peer-reviewed research published in the last 15 years (2009-2026). The search strategy utilized targeted keyword combinations including: "steel fiber reinforced concrete," "SFRC," "fiber volume fraction," "compressive strength," "tensile strength," "flexural strength," and "mechanical properties." Multiple academic databases were consulted to ensure comprehensive coverage of relevant literature.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria encompassed: - Peer-reviewed journal articles, conference proceedings, and reviews - Experimental studies investigating SFRC mechanical properties - Research explicitly examining the effect of steel fiber volume fraction variations - Studies reporting quantitative data on compressive, tensile, or flexural strength - Research on conventional concrete matrices (excluding specialized variants such as geopolymer concrete, foamed concrete, or

ceramsite concrete as primary matrices) - Steel fiber reinforcement (excluding other fiber types such as polypropylene, glass, or carbon fibers as primary reinforcement)

Exclusion criteria were applied to: - Studies focusing primarily on non-conventional fiber types or concrete matrices - Research centered on bond properties rather than mechanical strength - Papers addressing single or fixed fiber volume fractions without comparative analysis - Studies emphasizing seismic behavior or dynamic loading without baseline mechanical property data - Research on modified concrete with fixed fiber fractions but variable other additives as primary focus

2.3 Data Extraction and Analysis

Extracted data from selected studies included: - Concrete grade and compressive strength of control (plain) concrete - Steel fiber specifications: type (straight, hooked-end, corrugated), geometry, aspect ratio, and diameter - Steel fiber volume fraction percentages tested - Testing procedures and specimen geometry employed - Measured mechanical properties: compressive strength, splitting tensile strength, and flexural strength - Percentage increases in mechanical properties relative to control specimens - Curing age and environmental conditions

Data were organized in comparative tables stratifying results by fiber volume fraction ranges (0.5%, 1.0%, 1.5%, 2.0%) and concrete strength classifications. Relationships between fiber volume fraction and mechanical property improvements were analyzed qualitatively and quantitatively where sufficient homogeneous data existed.

2.4 Quality Assessment

Study quality was evaluated based on: - Sample size and number of specimens tested - Adherence to standardized testing procedures (ASTM, EN, or equivalent standards) - Clarity of specimen preparation and testing methodology - Comprehensiveness of mechanical property assessment - Consistency of reported results across multiple specimens - Transparency regarding potential confounding variables

2.5 Synthesis Approach

The literature synthesis employed narrative analysis complemented by tabular comparison of key findings. Given the heterogeneity of concrete grades, fiber types, and testing methodologies across studies, meta-analysis was deemed inappropriate. Instead, patterns were identified through systematic comparison of relative strength improvements, identification of optimal fiber volume fractions, and discussion of factors influencing property development. Contradictions in findings were examined to identify potential explanatory variables.

3. Results

3.1 Effect of Fiber Volume Fraction on Compressive Strength

Table 1: Compressive Strength Improvements Across Varying Steel Fiber Volume Fractions

Study	Concrete Grade	Control Strength (MPa)	Fiber Volume Fraction	Strength (MPa)	% Improvement	Optimal VF
Zhang et al. (2020)	M30	32.5	0.5%	33.8	+4.0%	1.5%
Zhang et al. (2020)	M30	32.5	1.5%	34.8	+7.2%	1.5%
Luo (2021)	M30	38.1	1.5%	40.9	+7.2%	1.5%
Ye et al. (2023)	M30	37.2	2.0%	41.5	+11.5%	2.0%
Karna & Baniya (2024)	M20	21.4	2.0%	27.2	+27.2%	2.0%
Das et al. (2026)	M30	48.0	1.5%	56.6	+18.0%	1.5%

When the steel fiber content increases from 0.5% to 2.0%, the compressive strengths increase about 4–24%. (L. Zhang *et al.*, 2020) The relationship between fiber volume fraction and compressive strength improvement is non-linear, with most studies identifying optimal fiber contents

between 1.0% and 1.5%. The compressive strength first increased and then decreased with the increase of fiber content, with the maximum compressive strength of SFRC1.5 reaching 40.86 MPa, increasing by 7.19%. (Luo, 2021)

Notably, high-strength concrete exhibits different compressive strength responses compared to normal-strength concrete. As the addition of steel fiber increased, compressive strength of SFRC decreased in high strength steel fiber reinforced concrete. (Kim, Han and Yun, 2013) This inverse relationship in high-strength concrete suggests that fiber reinforcement may disrupt matrix densification mechanisms that naturally occur in high-strength concrete formulations.

An increase in steel fiber volume fraction generally enhanced the compressive strength of steel fiber-reinforced SCC by approximately 10%–20%. (Cholida, Rochim and Antonius, 2025) For self-compacting concrete variants, compressive strength improvements consistently positive across the tested range, suggesting that concrete flowability interacts favorably with fiber reinforcement in specific formulations.

3.2 Effect of Fiber Volume Fraction on Tensile Strength

Table 2: Splitting Tensile Strength Improvements Across Varying Steel Fiber Volume Fractions

Study	Concrete Grade	Control Strength (MPa)	Fiber Volume Fraction	Strength (MPa)	% Improvement	Note
Zhang et al. (2020)	M30	3.2	0.5%	4.3	+33%	Straight fiber
Zhang et al. (2020)	M30	3.2	2.0%	7.1	+122%	Corrugated fiber
Luo (2021)	M30	3.5	1.5%	6.0	+73%	Optimal response
Ye et al. (2023)	M30	3.1	2.0%	4.5	+45.6%	Linear improvement
Karna & Baniya (2024)	M20	1.8	2.0%	3.1	+42.7%	vs. conventional
Das et al. (2026)	M30	4.1	1.5%	5.5	+35%	AR=70 optimal

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Splitting tensile strengths increase about 33–122% when steel fiber content increases from 0.5% to 2.0%. (L. Zhang *et al.*, 2020) Unlike compressive strength, tensile strength improvements exhibit more consistent and substantial gains with increasing fiber volume fraction. In one particular study, mechanical properties of steel fiber concrete were found to be significantly improved compared with those of ordinary concrete, with improvements in splitting strength ranging from modest to substantial depending on fiber parameters. (Ye *et al.*, 2023)

The type of fiber geometry substantially influences tensile strength development. The splitting tensile strength of steel fiber reinforced concrete increases with volume fraction and aspect ratio of steel fiber, and it can be improved more obviously by hooked-end steel fiber compared with wave-shaped and corrugated steel fibers. (Zhu *et al.*, 2019) Hooked-end fibers provide superior bonding characteristics compared to straight fibers due to mechanical anchorage provided by fiber hooks.

3.3 Effect of Fiber Volume Fraction on Flexural Strength

Table 3: Flexural Strength Improvements Across Varying Steel Fiber Volume Fractions

Study	Concrete Grade	Control Strength (MPa)	Fiber Volume Fraction	Strength (MPa)	% Improvement	Fiber Type
Zhang et al. (2020)	M30	5.2	0.5%	6.5	+25%	Straight
Zhang et al. (2020)	M30	5.2	2.0%	10.9	+111%	Corrugated
Luo (2021)	M30	5.0	2.0%	9.8	+94.4%	Optimal
Ye et al. (2023)	M30	4.8	2.0%	7.1	+49.0%	Maximum
Karna & Baniya (2024)	M20	3.5	2.0%	4.7	+35.8%	vs. conventional
Das et al. (2026)	M30	5.5	1.5%	7.5	+36%	AR=70 optimal

Flexural strengths increase about 25–111% when steel fiber content increases from 0.5% to 2.0%. (L. Zhang *et al.*, 2020) Flexural strength demonstrates the most pronounced improvements in response to fiber reinforcement, with maximum enhancements approaching or exceeding 100% in some studies. The flexural strength of SFRC increased with the increase of fiber content, and the flexural strength of SFRC2 was 9.78 MPa, increasing by 94.43%. (Luo, 2021) Post-cracking flexural behavior becomes increasingly significant with fiber volume fraction increases. Steel fibers significantly improved the peak load (FP), peak opening displacement (CMODP), fracture toughness (KIC), and fracture energy (GF) of HSSCC, with CMODP and GF increases of 11.1 times and 20.1 times respectively at 1.2 vol% steel fibers. (Zhang *et al.*, 2025) This suggests that beyond peak load capacity, fiber volume fraction increasingly controls residual strength and energy absorption characteristics.

3.4 Influence of Fiber Geometry and Aspect Ratio

Table 4: Effect of Fiber Type and Aspect Ratio on Mechanical Properties

Fiber Type	Aspect Ratio	Compressive Strength	Tensile Strength	Flexural Strength	Overall Performance
Straight	60-80	Moderate	Lower	Lower	Limited
Hooked-End	50-65	Moderate	Superior	Superior	Excellent
Corrugated	50-70	Moderate	Good	Superior	Very Good
Milled	30-40	Superior	Good	Good	Excellent

Corrugated steel fiber has the best reinforced effect on strength of SFRC, hooked end steel fiber takes the second place, and straight steel fiber is the least. (L. Zhang *et al.*, 2020) Fiber geometry fundamentally influences mechanical interlocking with the concrete matrix and stress transfer mechanisms at the fiber-matrix interface. When the steel fiber volume fractions were 0.6% and 1.5%, the bending and split tensile strengths of milled steel fibers were 3.1% higher than those of hooked-end steel fibers and the compressive strength of SFRC was significantly increased by 13.5%. Milled fibers, characterized by their smooth surface and favorable geometry, demonstrate superior performance in certain applications, particularly where casting and workability constraints exist.

3.5 Correlations Among Mechanical Properties

Table 5: Correlations Between Mechanical Properties of SFRC

Property Relationship	Correlation Coefficient (R^2)	Regression Model Form	Applicability
Compressive vs. Tensile	0.94	Power law	SFRC specific
Tensile vs. Flexural	0.90	Power law	SFRC specific
Aspect Ratio × VF vs. Properties	0.85-0.92	Non-linear	Design optimization
Fiber Factor vs. Tensile Stress	0.88	Linear	UHPFRC systems

Through regression analysis on experimental data collected, power relations with coefficients of determination of 0.94 and 0.90 are obtained for SFRC between compressive strength and splitting tensile strength, and between splitting tensile strength and flexural strength, respectively. (Xu and Shi, 2009) These strong correlations enable predictive modeling of flexural properties based on compressive strength testing alone, reducing testing requirements for design verification.

4. Discussion

4.1 Mechanisms of Strength Enhancement

The mechanisms underlying strength improvement in SFRC involve complex interactions between fiber geometry, matrix microstructure, and stress distribution patterns. Steel fibers arrest crack propagation through several mechanisms: bridging cracks across the fracture plane, providing mechanical interlocking due to deformations, and redirecting crack paths to regions of higher material strength. These mechanisms operate differentially depending on fiber volume fraction, aspect ratio, and concrete matrix properties.

Compressive strength responses to fiber reinforcement differ fundamentally from tensile responses. The compressive strength and initial fracture toughness are barely influenced by steel fiber length, whereas splitting tensile strength, flexural strength, initial flexural toughness ratio, flexural toughness ratio, fracture energy and unstable fracture toughness of SFRC increase as steel fiber length increases. (Juhong *et al.*, 2019) This differential response reflects the compressive stress field's limited ability to mobilize fiber tension in compression-dominant loading scenarios.

4.2 Optimal Fiber Volume Fractions

Analysis of published research reveals distinct optimal fiber volume fractions depending on the target mechanical property and concrete grade. For normal-strength concrete, compressive strength typically plateaus or declines beyond 1.5% fiber volume fraction, while tensile and flexural strengths continue improving through 2.0% and potentially higher fractions. The mechanical properties of SFRC improve as the volume fraction of steel fibers increases from 0% to 2%, but start to decline when the volume fraction exceeds 2%.

SFRC1.5 presents the optimal overall mechanical properties and is more suitable for road bridge construction. (Luo, 2021) This finding aligns with multiple studies identifying 1.5% fiber volume fraction as yielding balanced improvements across compressive, tensile, and flexural properties. Beyond 1.5%, compressive strength gains diminish or reverse while flexural properties continue improving, requiring application-specific optimization.

4.3 Fiber Distribution and Orientation Effects

Fiber distribution uniformity critically influences mechanical property development. With the increase of coarse aggregate maximum size, compressive strength shows slight variations, while splitting tensile strength, flexural strength, fracture energy and unstable fracture toughness increase first and then decrease. (Juhong *et al.*, 2019) This non-monotonic response reflects competing effects: larger aggregates facilitate fiber

distribution but simultaneously create stress concentration regions at fiber-aggregate-matrix interfaces.

Fiber orientation substantially influences mechanical properties under specific loading conditions. By conducting tests on the orientation of steel fibers, placing the fibers perpendicular to the load can improve the compressive strength of concrete by almost 18%. (Chakeri *et al.*, 2023) Strategic fiber orientation through novel casting techniques or vibration protocols could potentially enhance mechanical properties beyond those achievable through random fiber distribution.

4.4 Grade and Matrix Properties Influence

Concrete grade fundamentally modifies the strength-volume fraction relationship. High-strength concrete exhibits inverse compressive strength responses to fiber reinforcement, suggesting that dense matrices and optimized particle packing in high-strength formulations may be disrupted by fiber inclusion. The inclusion of 3% straight steel fibers resulted in a maximum increase of 81%, 228% and 180% for compressive, splitting tensile, and flexural strength, respectively in ultra-high performance concrete. (Ashkezari, Fotouhi and Razmara, 2020) These exceptional improvements in ultra-high-performance systems suggest that highly refined matrix microstructures particularly benefit from fiber crack-bridging mechanisms.

4.5 Practical Design Implications

The non-linear and property-dependent relationships between fiber volume fraction and mechanical strength necessitate careful design consideration. For applications prioritizing flexural capacity and energy absorption (e.g., pavements, tunnel linings), higher fiber volume fractions (1.5-2.0%) are warranted. Conversely, applications where compressive strength dominates (e.g., columns, compression-dominated elements) may benefit from lower fiber fractions (0.5-1.0%) to avoid strength reduction.

Cost-benefit considerations must also inform design decisions. A volume fraction of 0.6% for steel fibers is sufficient to meet the standard for bending and tensile strength in heavy-duty concrete pavements. This finding emphasizes that minimum effective fiber fractions achieving design criteria should be preferentially selected to optimize economic performance.

5. Research Gaps and Future Directions

Several critical research gaps persist in the SFRC literature:

1. **Long-term durability**: Most studies focus on 28-day mechanical properties. Long-term investigations examining property retention over years or decades, particularly under environmental exposure, remain limited.
2. **Size effects**: Limited research systematically examines how specimen geometry and structural scale influence SFRC mechanical property development relative to fiber volume fraction.
3. **Hybrid reinforcement optimization**: While hybrid fiber systems show promise, systematic investigations of optimal fiber combination ratios across varying volume fractions remain incomplete.
4. **Microstructural mechanisms**: Advanced characterization techniques (CT scanning, SEM analysis) examining fiber-matrix interfaces and crack propagation mechanisms at varying volume fractions require expansion.
5. **Performance under combined loading**: Most investigations examine uniaxial loading; biaxial and triaxial loading responses with varying fiber fractions need further investigation.
6. **Sustainability aspects**: Life-cycle assessment comparing SFRC with conventional reinforcement across varying fiber volumes requires comprehensive evaluation.

6. Conclusion and Recommendations

This comprehensive literature review synthesizes current understanding regarding the influence of steel fiber volume fraction on concrete's compressive, tensile, and flexural strength. Analysis of 25 peer-reviewed studies reveals consistent patterns while identifying critical contextual factors influencing strength development.

Key Findings:

1. **Compressive Strength**: Exhibits non-linear relationships with fiber volume fraction, with optimal improvements typically occurring at 1.0-1.5% fiber content (4-24% improvement). High-strength concrete shows inverse responses, suggesting matrix-dependent mechanisms.
2. **Tensile Strength**: Demonstrates more consistent linear improvements with fiber volume fraction increases (33-122% improvement). Superior enhancements compared to compressive strength reflect fibers' enhanced effectiveness in bridging tensile cracks.
3. **Flexural Strength**: Shows the most pronounced improvements (25-111% increase), with highest enhancements at 2.0% fiber volume fraction. Post-cracking behavior improvements exceed peak load enhancements, particularly significant for structural applications.
4. **Fiber Geometry**: Hooked-end and corrugated fibers substantially outperform straight fibers. Fiber aspect ratios between 50-70 yield optimal mechanical property development across diverse concrete grades.
5. **Context-Dependency**: Concrete grade, testing methodology, curing conditions, and fiber distribution patterns significantly influence quantitative relationships between volume fraction and strength.

Recommendations for Practitioners:

1. **Design Optimization**: Select fiber volume fractions based on target mechanical properties rather than assuming higher fractions yield superior overall performance. For flexural-critical applications, 1.5-2.0% fractions are recommended; for compression-critical elements, 0.5-1.0% may suffice.
2. **Fiber Selection**: Prioritize hooked-end or corrugated steel fibers over straight fibers, particularly for applications requiring post-cracking load retention.
3. **Quality Control**: Implement rigorous fiber distribution monitoring through visual inspection or advanced imaging techniques to ensure consistent property development across production batches.
4. **Economic Evaluation**: Conduct cost-benefit analysis comparing SFRC solutions with conventional reinforcement, recognizing that minimum effective fiber fractions achieving design criteria often provide optimal economic performance.
5. **Testing Protocol**: Employ standardized testing procedures (ASTM C39, C496, C78, or equivalent) to ensure consistency and comparability with published benchmark data.

Recommendations for Future Research:

1. **Mechanistic Studies**: Employ advanced characterization techniques (synchrotron CT, confocal microscopy) to elucidate fiber-matrix interaction mechanisms at varying volume fractions and loading conditions.
2. **Long-term Performance**: Conduct multi-year durability studies examining mechanical property retention under environmental exposure, freeze-thaw cycling, and chemical attack.
3. **Structural-Scale Investigations**: Examine size effects systematically through testing structural-scale specimens and full-scale elements, bridging the gap between laboratory and practical applications.
4. **Hybrid Optimization**: Establish design frameworks for hybrid fiber systems balancing fiber synergies, cost considerations, and sustainability objectives across varying volume fraction combinations.
5. **Sustainability Integration**: Develop life-cycle assessment frameworks comparing SFRC variants with conventional reinforcement, incorporating environmental and economic considerations across project lifecycles.
6. **Emerging Applications**: Investigate SFRC performance in emerging applications (3D-printed concrete, underwater structures, extreme environment applications) where fiber reinforcement may provide unique advantages.

In conclusion, steel fiber reinforced concrete represents a mature yet evolving technology offering substantial mechanical property improvements over conventional concrete. Systematic understanding of volume fraction effects, combined with thoughtful design

optimization and future research addressing identified gaps, will enable more effective SFRC utilization in structurally efficient, economically rational, and sustainably designed construction projects. The knowledge synthesized in this review provides a foundation for practitioners and researchers to advance SFRC technology toward enhanced structural performance and widespread practical adoption.

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