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Experimental Investigation of Steel Fiber Diameter, Volume Fraction, and Aspect Ratio on Concrete Mechanical Behavior

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ABSTRACT Concrete is the most widely used construction material due to its versatility and ability to be molded into various shapes. However, it inherently exhibits little tensile strength, limited ductileness, and poor crack resistance, often leading to brittle failure. To address these limitations, modern construction increasingly incorporates fibers into concrete to enhance its mechanical properties, durability, and overall performance. Among various fiber types, steel fibers have demonstrated superior crack resistance and improved structural behavior. This study focuses on evaluating the flexural strength behavior of Steel Fiber Reinforced Concrete (SFRC) using M30 grade concrete. An experimental program was conducted involving the casting of 180 prisms (100 × 100 × 500 mm) and 360 cubes (100 × 100 × 100 mm) with steel fiber contents of 1%, 1.5%, and 2% and aspect ratios of 50, 60, and 70. The fiber used had a diameter of 1 mm. The experimental program was limited to evaluating the mechanical performance of the concrete using compressive strength, flexural strength, and splitting tensile strength tests. Special tamping. micromechanical analysis and different workability methods have been omitted. The results reveal that incorporating steel fibers significantly enhances the mechanical properties of concrete. Notably, a mix containing 1.5% steel fibers with an aspect ratio of 70 exhibited the highest strength improvements across all tests, including an 18% increase in compressive strength, a 35% increase in split tensile strength, and a 36% increase in flexural strength compared to control specimens. These findings demonstrate that optimized steel fiber reinforcement not only improves flexural behavior but also contributes to superior structural integrity, making SFRC a promising material for high-performance construction applications.

KEYWORDS Steel Fiber Reinforced Concrete (SFRC); Flexural Strength; Aspect Ratio; Mechanical Properties; M30 Grade Concrete.

1 INTRODUCTION

Concrete is the most extensively used building material due to its versatility and ability to replace traditional materials like stone and brick. Its strength and durability can be enhanced by adjusting mix components—cement, water, and aggregates—and adding specialized ingredients. However, it has limitations, including low tensile strength, brittleness, limited ductility, and poor fatigue and impact resistance (Shende and Pande, 2012; Shetty, 2021).

Concrete naturally contains microcracks that propagate under load, leading to brittle failure (Khamees et al., 2020). Even before loading, drying shrinkage and volume changes can cause microcracks. Researchers have improved concrete tensile behavior by using additional reinforcement methods.

Incorporating discrete, uniformly distributed fibers improves both stationary and dynamic properties of concrete. Fiber-reinforced concrete (FRC) includes materials like steel, glass, carbon, polypropylene, coir (coconut) fiber, and nylon. Fibers are defined through their aspect ratio (length/diameter), typically between 30–150 (Khamees et al., 2020). Performance depends on fiber type, geometry, distribution, and bonding with the matrix (Rana, 2013).

Steel fibers, commonly used in FRC, enhance flexural, fatigue, and impact strength despite minor rusting issues. They are widely used in pavements, bridge decks, and thin structural elements (Vairagade and Kene, 2013). Interfacial bonding, critical for performance, can be improved through surface treatments.

FRC offers isotropic strength, improved fatigue resistance, and energy absorption, making it suitable for airfields, industrial floors, bridge decks, ducts, and prefabricated elements (Neeraja, 2013). "Wirand Concrete" is a trade name for SFRC, commonly used in the U.S.

Historically, fiber like straw and horsehair were used in construction. Modern fiber-reinforced concrete emerged in the 1950s, with extensive research continuing today (Naaman, 2018). Studies show SFRC improves compressive and tensile strength by 5–20%, flexural strength by 20–65%, and elastic modulus by 5–25%, depending on fiber content (1–8%) and aspect ratio (50–100%) (Shende and Pande, 2012; Khamees et al., 2020).

The field of fiber strengthening mechanics advanced significantly with Romualdi's work in the early 1960s, where he introduced a fracture mechanics tactic to assess the breaking strength of masonry reinforced with closely spaced steel fibers (Romualdi and Batson, 1963). He also proposed a constitutive model to define the behavior of fiber-reinforced composites—an innovative step at the time.

Later, the flexural capability of Steel Fiber Reinforced Concrete (SFRC) was estimated using constitutive relationships, assuming a mostly linear interfacial bond between fibers and matrix (Swamy and Mangat, 1974). These models aligned well with experimental data but were limited to tension-hardening composites that can sustain increasing stress after cracking. To address this, Lim introduced a model combining both tension hardening and softening to better represent SFRC behavior (Lim et al., 1987).

Driven by the construction industry's demand for alternative materials, SFRC has gained use in industrial floors, pile-supported slabs, walkways, and tunnel linings. This has led to significant progress in SFRC constitutive modeling (Hillerborg, 1980; Barros and Figueiras, 1999; Bernard and Pircher, 2000; Soranakom et al., 2008).

Studies have consistently shown that steel fibers enhance the compressive, tensile, and flexural properties of concrete. The inclusion of hooked-end steel fibers improves post-cracking behavior and toughness (Ou et al., 2012; Ni et al., 2014) demonstrated how steel fibers increase ductility and strain capacity under compression.

Fiber aspect ratio besides geometry has a pronounced impact on mechanical performance. Research by Liang et al. (2023) highlighted that higher aspect ratios improve flexural strength but reduce workability. Khamees et al. (2020) emphasized the synergistic properties of fiber length and type on compressive and splitting tensile strength.

Fiber volume fraction significantly affects crack control and energy dissipation. Studies by Iqbal Khan and Abbas (2023) and Kim et al. (2021) confirm that increasing fiber volume improves both compressive and flexural strengths up to an optimal limit. However, exceeding this limit can lead to reduced workability and fiber clustering (Sable and Rathi, 2012).

SFRC is resistant to environmental degradation due to improved crack control and matrix densification. Zheng et al. (2024) examined durability indicators such as chloride permeability and freeze-thaw resistance and observed significant improvements in hybrid fiber systems. Confirmed long-term performance under aggressive conditions.

Despite its strength advantages, SFRC suffers from reduced workability. Xu et al. (2024) and Sivanantham et al. (2022) found that workability declines with higher fiber content, especially with long or hooked fibers. Superplasticizers are often required to ensure homogeneity in mixes.

Several studies adopted statistical and numerical modeling techniques to optimize mix design and predict mechanical properties. Mir (2013) applied regression models to identify critical fiber parameters influencing strength. Ganapathy et al. (2022) utilized machine learning for reliable strength prediction.

Meta-analyses and large-scale datasets such as those presented by Garcia-Taengua et al. (2021) helped formulate predictive equations for SFRC flexural capacity.

Even though Steel Fiber Reinforced Concrete (SFRC) has advanced significantly, there are still several important research gaps that need to be filled. First off, while numerous research has investigated the impact of certain fiber parameters, such aspect ratio or volume fraction, very few have thoroughly investigated how these parameters combine to affect a variety of mechanical properties in a typical laboratory setting. Furthermore, there is disagreement on the best fiber arrangements, particularly for uses like precast elements, pavements, or slabs. Efforts to create unifying design guidelines are made more difficult by inconsistent experimental procedures and findings with inadequate reproducibility.

Furthermore, workability issues brought on by longer or larger fiber volumes are frequently mentioned but not statistically examined in relation to mechanical performance, which creates real-world implementation obstacles. Additionally, there is a dearth of experimental data relevant to a given region, especially from developing countries where economic constraints, material availability, and construction procedures differ from those expected in much international research.

To fill these gaps, this study examines how the volume fraction and steel fiber aspect ratio interact to affect the concrete's flexural, splitting tensile, and compressive strengths. To evaluate mechanical behavior across various fiber topologies and take workability concerns into account, the research used a methodical experimental methodology.

This study not only closes a significant research gap but also provides a methodical examination of how steel fiber diameter, aspect ratio, and volume fraction interact to affect compressive, tensile, and flexural strength in M30-grade concrete under identical mixing and curing protocols. If recent papers such as Zhao et al. (2023) and Veeramanikandan et al. (2023) are studied, synergistic effects of all parameters combined still need to be studied. This paper helps to identify deviations and suggest improvements by validating and improving current predictive models using high-fidelity experimental data. The knowledge gained also lays the foundation for future simulation and machine-learning techniques to predict SFRC behavior, connecting theoretical developments with practical engineering applications. These insights provide practical mix-design guidelines for optimizing SFRC performance in resource-constrained construction environments like Bangladesh.

2 METHODS

To ascertain the effects of steel fiber on concrete, this research program includes an examination of the literature and experimental analyses. Control specimens and SFRC were cast, and 30 grade concrete was chosen as most of the construction works here in Bangladesh uses 20–40 MPa concrete.

2.1 Selection of Steel Fiber Parameters

For this study we selected steel fiber contents of 1.0, 1.5 and 2.0%, diameters 0.5 mm and 1.0 mm, and aspect ratios 50, 60 and 70 because these ranges are commonly used in experimental investigations and represent a practical compromise between enhanced crack-bridging/post-crack toughness and acceptable workability (Choi et al., 2019; Biswas et al., 2021; Yusuf et al., 2023). These parameters enable a systematic assessment of how fiber slenderness and dosage influence tensile, flexural and post-cracking behavior, while the two diameters allow evaluation of the trade-off between fiber dispersion (favored by finer fibers) and individual fiber pull-out resistance (favored by coarser fibers). Based on prior work, we expect increased volume fraction and aspect ratio to improve toughness and residual strength but to reduce fresh-state workability — an effect mitigated here through controlled mixing and admixture use (Gao et al., 1997; Biswas et al., 2021). Also, if thought economically, steel fibers within the 1.0–2.0% volume range are economically viable for local infrastructure projects, where cost-efficiency and material availability are critical also mentioned in in ACI 544.4R-18, which emphasizes the use of microfibers in the range of 0.5–2.0% by volume for structural applications such as slabs-on-ground, precast elements, and tunnel linings (American Concrete Institute, 2018).

2.2 Specimen types

Specimen sizes of 100 × 100 × 100 mm cube and 100 × 100 × 500 mm beam were selected. The test specimens after casting were subjected to plain water curing for 7 days, 14 days and 28 days. The specimens underwent a series of destructive tests to determine their strength after the specific exposure period. Workability test and three destructive tests: of i) cube compressive strength; ii) cube splitting tensile strength; iii) beam flexural strength were conducted in the experimental program discussed in section 2.5.

2.3 Materials

The materials were tested to ensure proper mix design and integrity of the work. The tests results of those materials is discussed in this section.

2.3.1 Cement

According to ASTM C150 (ASTM C01 Committee, 2022) Type I specifications, Ordinary Portland Cement (OPC) was employed in the investigation. The physical and chemical characteristics are listed in Table 1 and Table 2 respectively.

Table 1. Physical properties of portland cement used

Characteristics	Results
0.075 mm (200 Sieve) passing (%)	94
Blaine Specific surface (cm^2/g)	3,030
Normal Consistency (%)	26
Soundness (mm)	7
Initial Setting Time (minutes)	155
Final Setting Time (minutes)	225
Specific Gravity	3.07
Compressive Strength 3-days (MPa)	15.3
Compressive Strength 7-days (MPa)	23.8
Compressive Strength 28-days (MPa)	31.1

All of the values of our OPC fall under the guidelines prescribed in the ASTM C150.

2.3.2 Coarse Aggregate

In this study, coarse aggregate in the form of quartzite rock chips was utilized. In this investigation, stone chips were collected from ready mix concrete company. The coarse aggregate's maximum nominal size was 20

Table 2. Portland cement's chemical compositions used

Oxide	Common Name	Results (%)
CaO	Lime	63.49
SiO_2	Silica	21.01
Al_2O_3	Alumina	5.80
Fe_2O_3	Ferric oxide	3.60
MgO	Magnesia	1.46
K_2O	Alkalis	0.87
Na_2O	Alkalis	0.87
SO_3	Sulfur trioxide	2.56
CO_2	Carbon dioxide	—
H_2O	Water	0.07
Bogue's Potential Compound Composition:		
$3CaO.SiO_2$	Tricalcium silicate	47.38
$2CaO.SiO_2$	Dicalcium silicate	24.51
$3CaO.Al_2O_3$	Tricalcium aluminate	9.28
$4CaO.Al_2O_3.Fe_2O_3$	Tetracalcium aluminoferrite	10.95

mm. The Coarse aggregate properties are tabulated in Table 3.

Table 3. Properties of coarse aggregate

Properties	Result
Specific gravity	2.75
Unit weight (kg/m^3)	1,560
Absorption capacity (%)	0.70
Total moisture (%)	0.28

2.3.3 Fine Aggregate

Concrete has been made with Sylhet sand, a good quality sand as the fine aggregate. Table 4 provides the pertinent properties of fine aggregate. In the Figure 1, the grain size distribution of fine aggregate and coarse aggregate is shown.

2.3.4 Water

The quality of water has a considerable impact on concrete preparation. Water contaminants can reduce concrete strength and durability while also interfering with the cement's ability to set. The quality records of test results provide information about the suitability of the water. Total solids, pH, chloride, hardness, dissolved oxygen, turbidity etc. were checked to ensure that the water was potable.

Table 4. Properties of fine aggregate

Properties	Fine Aggregate
Fineness modulus	2.58
Specific gravity	2.61
Unit weight (kg/m^3)	1,495
Absorption capacity (%)	1.5
Total moisture (%)	0.9
Chloride content (%)	0.004
Sulfate content (%)	0.005

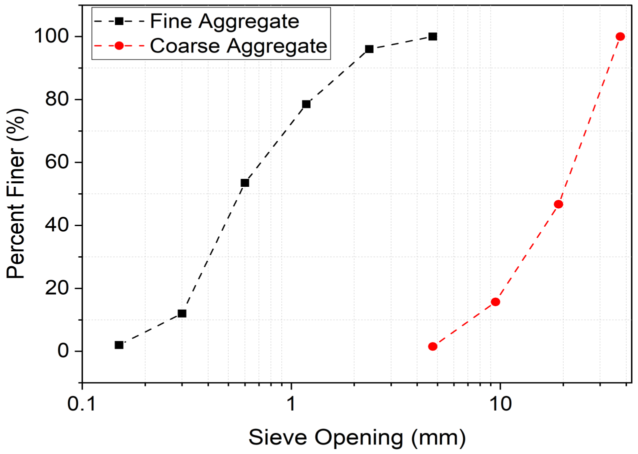

Figure 1. Grain size distribution curve of fine and coarse aggregate.

2.3.5 Steel Fiber

Steel fiber is a small carbon, cold-drawn wire fiber mass-produced in compliance with ASTM A820/A820M (ASTM A01 Committee, 2022). Steel fibers deliver higher energy absorption and rises concrete ductibility. Readily available steel fiber was collected from the local market and then cut it into different lengths as per aspect ratio. The steel fiber utilized in this investigation is shown in Figure 2.

Figure 2. Steel fiber used in this investigation.

2.4 Mix Design and Ratio

To determine the ratio of constituents ACI 211.1-91 mix design was followed (American Concrete Institute, 2009). In this investigation, SF has been utilized. By weight of the total mix, steel fiber was added to the concrete. Three different percentages of steel fiber i.e., 1%, 1.5% and 2% were used by weight. For comparison, a concrete mix of 100% OPC was included in this program. A particular mix ratio was used for making the test specimen. Specimens of Ordinary Portland Cement (OPC) concrete were created and subjected to an ordinary water environment. The concrete test specimens were made with varying percentages of steel fiber. The various test variables including different materials are listed below.

Table 5. Mix proportion of the concrete

Mixture Constituent	Properties
Grade of Concrete (MPa)	30
Cement (kg/m^3)	435
Sand (kg/m^3)	545
Stone Chips (kg/m^3)	1,150
Water Cement Ratio	0.45
Water (kg/m^3)	195.75

The concrete mixture was prepared by thoroughly blending coarse aggregate, portland cement, steel fiber, and fine aggregate, followed by one minute of dry mixing before gradually adding water. After three more minutes of mixing, the mixture was poured to create 540 specimens (180 prisms and 360 cubes). Each specimen was cast in two equal layers and manually compacted using a 16 mm diameter, 0.45 m long tamping rod with 25 blows per layer. In this study, no special methods were applied for tamping. It was done as cautiously as it could be done to limit entanglement of the fiber. After 24 hours, they were demolded and cured in plain water for 7, 14, and 28 days, after which they were tested at different ages as per the test program.

For sample declaration, a common theme was prescribed: First term represent steel fiber Diameter (mm), 2nd term “SFRC” represent Steel Fiber Reinforce Concrete, 3rd term represent steel fiber % and last term represent Aspect Ratio.

Similarly, 9 more ratios were chosen using 1 mm diameters wire and changing the fiber percentage and aspect ratio as shown as in Table 6.

Table 6. Sample designation

Designation	Constituents
0SFRC0.0(0)	Concrete without steel fiber
0.5SFRC1.0(50)	0.5mm diameters, SFRC, 1.0%, AR= 50
0.5SFRC1.0(60)	0.5 mm diameters, SFRC, 1.0%, AR= 60
0.5SFRC1.0(70)	0.5 mm diameters, SFRC, 1.0%, AR= 70
0.5SFRC1.5(50)	0.5 mm diameters, SFRC, 1.5%, AR= 50
0.5SFRC1.5(60)	0.5 mm diameters, SFRC, 1.5%, AR= 60
0.5SFRC1.5(70)	0.5 mm diameters, SFRC, 1.5%, AR= 70
0.5SFRC2.0(50)	0.5 mm diameters, SFRC, 2.0%, AR= 50
0.5SFRC2.0(60)	0.5 mm diameters, SFRC, 2.0%, AR= 60
0.5SFRC2.0(70)	0.5 mm diameters, SFRC, 2.0%, AR= 70

2.5 Mechanical Strength Tests

2.5.1 Compressive Strength

The most crucial factor in predicting how well concrete will work is its compressive strength. Utilizing a digital compression machine in agreement with BS 1881-116:1983 (British Standards Institution, 1983), the concrete cube compressive strength was assessed. Loads were applied with a uniform rate other than casting faces. The concrete cube compressive strength (σ, MPa) was determined using the following expression:

$$\sigma = \frac{P}{A} \tag{1}$$

Where, P = the specimen's maximum load at failure (N), A = the machine's plunger's mean surface area in contact (mm^2).

2.5.2 Split Tensile Strength

An additional crucial factor for forecasting the tensile properties of concrete is cracking strength. It is also employed to assess concrete's shear resistance. The test yields more consistent results than other tests and is easy to administer. After setting up the standard test configuration for this test, as shown in Figure 3, the concrete splitting tensile strength was estimated using the same compressive strength equipment. The specimen's ultimate load was noted, and the concrete splitting tensile strength (f_{ct}, MPa) was then estimated using the formula provided by Bureau of Indian Standards (1999):

$$f_{ct} = \frac{2P}{\pi a^2} \tag{2}$$

Where, P = the specimen's maximum load at failure (N), a = dimension of the cube (mm^2).

Figure 3. Splitting test apparatus.

2.5.3 Flexural Strength

Beam flexural strength is one way to calculate concrete tensile strength. It is a measurement of a concrete beam's capacity to withstand bending at failure. After 28 days, it is measured by loading a specimen with dimensions of 100 mm by 100 mm by 500 mm. The ASTM C293 (2018) standard test methods (center-point-loading) were applied to ascertain the flexural strength of the concrete beam. Figure 4 depicts the beam testing setup that was utilized to ascertain the flexural strength. The specimen was continuously shock-free loaded. Up to the breaking point, the rate of application of the load was constant. The flexural strength (R, MPa) was calculated using the following formula:

$$R = \frac{PL}{BD^2} \tag{3}$$

Where, P = maximum load (N), L = distance between supports in (mm), B = width of the specimen (mm), D = thickness of the specimen (mm).

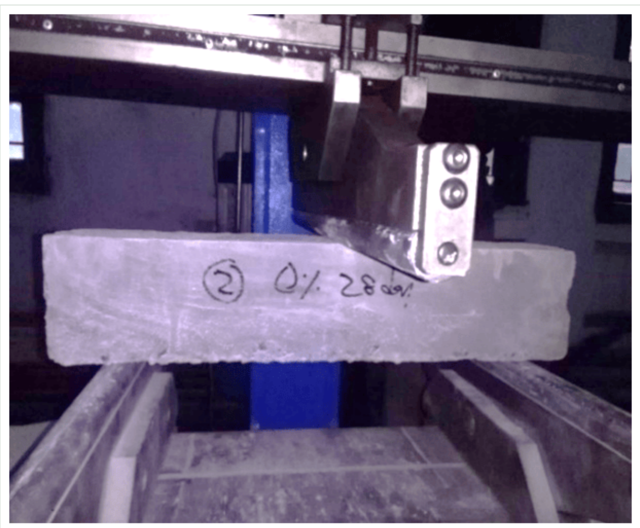

Figure 4. Flexural strength apparatus.

3 RESULTS

3.1 Workability

Figure 5 illustrates the slump values of SFRC compositions with different fiber diameters (0.5 mm and 1 mm). The slump value, which measures the workability of concrete, generally decreases as the fiber content increases. Concrete with 1 mm diameter fibers exhibits lower slump values compared to 0.5 mm fibers across all compositions, indicating reduced flowability with larger fibers. This research scope did not include other workability tests as it was not self-compacting concrete.

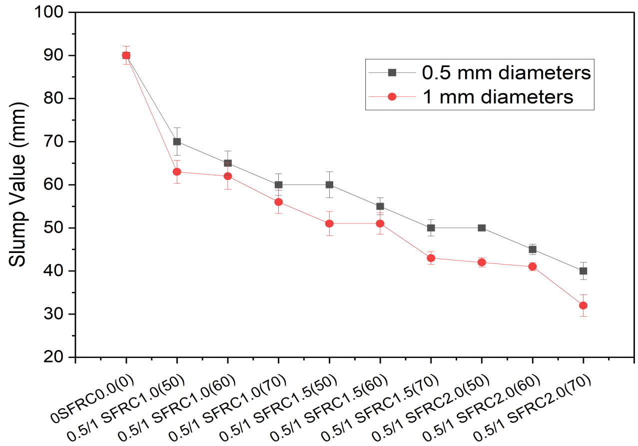

Figure 5. Slump values of different percentages of steel percentages.

The highest slump value is observed in the control sample (0SFRC0.0(0)), while the lowest occurs in specimens with 2.0% steel fibers and an aspect ratio of 70 (SFRC2.0(70)). This is a clear indication that increasing fiber content and aspect ratio negatively affects workability, requiring adjustments in mix design to maintain adequate flow while achieving desired improvements.

3.2 Compressive Strength

The Compressive strengths of SFRC and OPC concrete subjected to a plain water curing are shown graphically in Figure 6 and Figure 7. Steel Fiber Reinforced Concrete (SFRC) compressive strength was evaluated with varying steel fiber contents (1%, 1.5%, and 2%) over curing periods of 7, 14, and 28 days. All three tests were shown in the graph, but mean values were taken into consideration. The results demonstrated that adding steel fibers pointedly enhances compressive strength, with the most notable increase observed in specimens containing 1.5% steel fibers and an aspect ratio of 70, showing an 18% improvement over control samples. Compressive strength increased with both steel fiber content and aspect ratio, confirming that higher aspect ratios yield better reinforcement benefits.

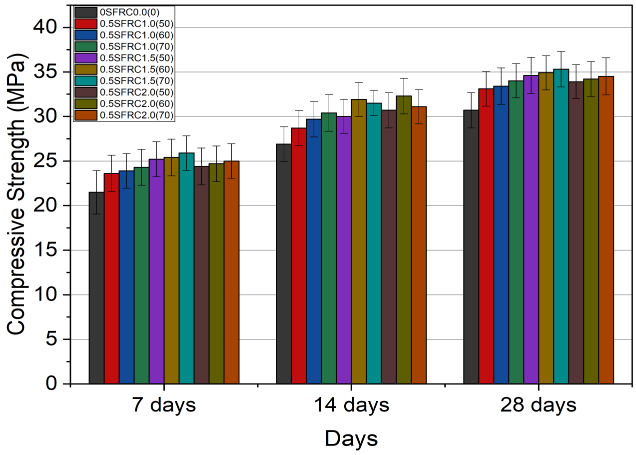

Figure 6. Compressive strength of varying percentage of 0.5 mm steel fiber, aspect ratios and curing periods.

At 14 days, specimens with 1%, 1.5%, and 2% steel fibers achieved higher compressive strength than the controller sample, with values ranging from 26.9 MPa to 32.3 MPa. After 28 days, the compressive strength further increased, reaching up to 36.3 MPa for specimens with 2% steel fibers. The consistent trend indicates that steel fibers enhance concrete's ability to resist compressive forces, making it a viable reinforcement material for construction applications. The synergistic effect of aspect ratio and fiber percentage has a good impact creating the maximum compressive strength.

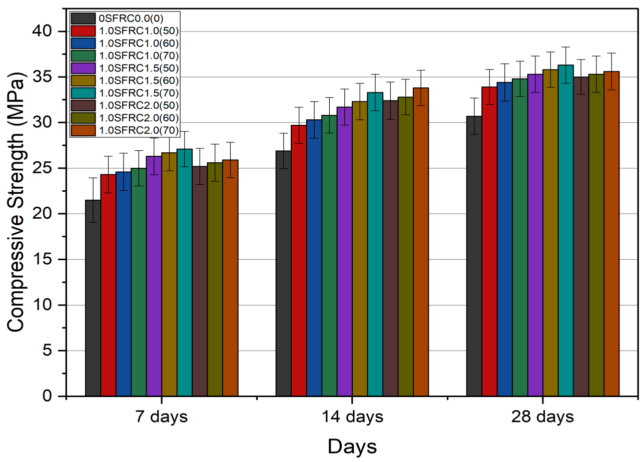

Figure 7. Compressive strength of varying percentage of 1 mm steel fiber, aspect ratios and curing periods.

ANOVA analysis for both the cases was checked. For the 0.5 mm and 1.0 mm steel fiber diameters, $p(< 0.05)$ values were found to be 0.0081 and 0.0001 respectively which is a clear indication that, some of the values have a significant change in strength which is consistent with the result.

These findings support are consistent with previous research, such as Shende and Pande (2012), which reported a 24% increase in flexural strength and (Mahadik et al., 2014), which documented a 19.5% improvement in compressive strength. Given the observed results, it is recommended to incorporate 1.5% steel fibers in concrete mixtures to maximize compressive strength, especially for applications requiring enhanced durability and load resistance.

The best performance in fiber-reinforced concrete is achieved at 1.5% fiber volume with an aspect ratio (AR) of 70, resulting from a synergistic balance of mechanical enhancement and fresh mix workability. At this dosage, the fiber density is adequate to bridge microcracks and delay macrocrack propagation, enhancing post-crack ductility and toughness while preventing fiber balling or segregation. The AR of 70 guarantees that fibers are long enough to create effective bond strength and anchoring inside the matrix, increasing pull-out resistance and energy absorption during fracture, but short enough to maintain uniform dispersion and minimize alignment difficulties.

3.3 Split Tensile Strength

Figure 8 and Figure 9 depict the comparison of SFRC and OPC subjected to normal curing for different days. The split tensile ability of Steel Fiber Reinforced Concrete (SFRC) was evaluated with varying steel fiber contents (1%, 1.5%, and 2%) after curing for 7, 14, and 28 days. The results indicate that specimens containing steel fiber consistently achieved higher split tensile strength than control samples, with the most significant improvement (+35%) observed in specimens with 1.5% steel fibers and an aspect ratio of 70. Strength values progressively increased with curing time, reaching up to 4.61 MPa at 28 days, demonstrating the reinforcing effect of steel fibers.

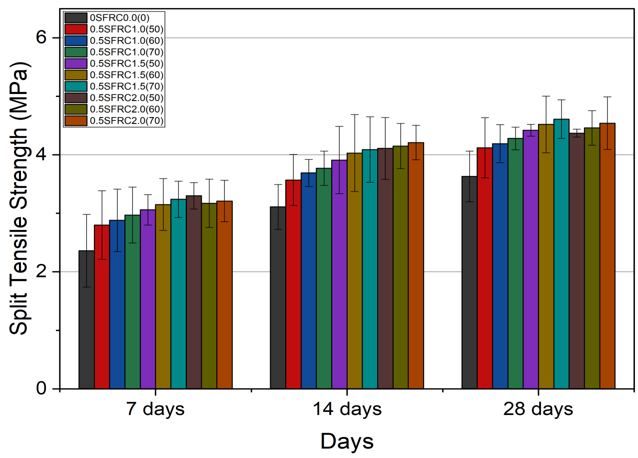

Figure 8. Split Tensile strength of varying percentage of 0.5 mm steel fiber, aspect ratios and curing periods.

At 7 days, split tensile strength ranged from 2.36 MPa to 3.3 MPa, while at 14 days, it improved further, reaching up to 4.21 MPa. The 28-day curing period yielded

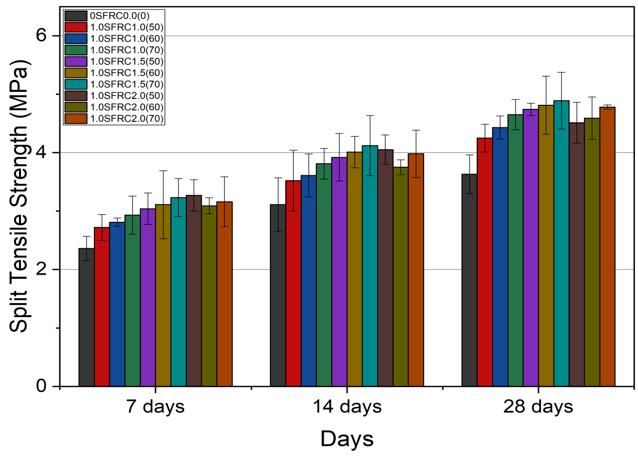

Figure 9. Split Tensile strength of varying percentage of 1 mm steel fiber, aspect ratios and curing periods.

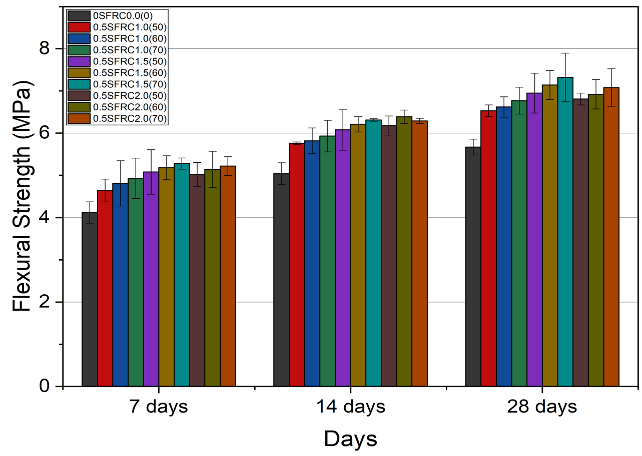

Figure 10. Flexural strength of varying percentage of 0.5 mm steel fiber, aspect ratios and curing periods.

the highest values, confirming that longer curing enhances fiber-reinforced concrete performance. Additionally, strength increases with higher aspect ratios, reinforcing the relationship between fiber distribution and load resistance. These results align with findings from (Shende and Pande, 2012), who reported a 41% increase in split tensile strength, supporting the effectiveness of steel fiber reinforcement. Given the observed improvements, incorporating 1.5% steel fibers by weight is recommended for maximizing split tensile strength, making SFRC a strong candidate for structural applications requiring enhanced durability and tensile resistance due to it's tensile strength.

From the ANOVA results both cases of fiber diameter had the *p*-values of 0.00061 and 0.00001 which proves the significance of ratios which are better than other ratios.

3.4 Flexural Strength

The flexural strengths of SFRC and OPC concrete subjected to plain water curing are shown graphically in Figure 10 and Figure 11. The flexural strength of Steel Fiber Reinforced Concrete (SFRC) was assessed with varying steel fiber contents (1%, 1.5%, and 2%) at curing periods of 7, 14, and 28 days. The results demonstrated a consistent increase in flexural strength with the inclusion of steel fibers, with the highest improvement (+36%) observed in specimens containing 1.5% steel fibers and an aspect ratio of 70. Strength values progressively increased over time, reaching up to 7.72 MPa after 28 days of curing, reinforcing the role of steel fibers in enhancing concrete performance.

At 7 days, flexural strength ranged from 4.12 MPa to 5.59 MPa, while at 14 days, the values improved further, reaching a maximum of 6.82 MPa. After 28 days, flexural strength peaked at 7.72 MPa, confirming the effectiveness of steel fiber reinforcement over extended

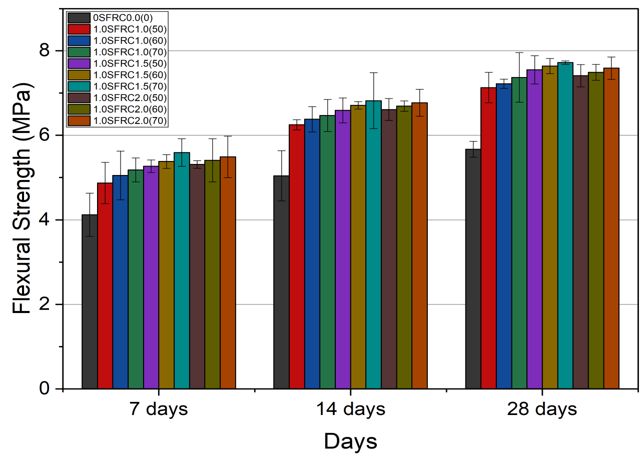

Figure 11. Flexural strength of varying percentage of 1 mm steel fiber, aspect ratios and curing periods.

curing periods. Additionally, strength increased with higher aspect ratios, highlighting the importance of fiber distribution and orientation in improving load resistance.

P-values from ANOVA showed values so low as 10^{-11} which determines that compressive strength is strongly dependent on the mix. Different fiber dosages give clearly different strengths. These findings align with previous research, including (Mahadik et al., 2014), which reported a 43.29% improvement in flexural strength. Based on the observed results, it is recommended to incorporate 1.5% steel fibers by weight in concrete to maximize flexural strength, making SFRC an optimal choice for applications requiring enhanced durability and bending resistance.

3.5 Correlations among SFRC Properties

Past research has used compressive and tensile strengths as key indicators for SFRC mechanical properties in structural design. The flexural and splitting tensile tests were preferred for measuring tensile strength due to their efficiency and cost-effectiveness compared to the direct tensile test. Several empirical equations are recommended by various researchers which are tabulated in Table 7. All empirical equations are nonlinearly correlated using power function, as shown in the following equation:

$$f_t = a(f_c')^b \quad (4)$$

where f_t (mm) is the tensile strength or flexural strength, f_c' (mm) is the compressive strength, and a and b are coefficients. Our experimental results are therefore fitted into this function to make such empirical equations.

Table 7. Concrete equation from previous research

Source	Equations
Compressive Strength and Tensile Strength Relations	
ACI 318 (American Concrete Institute, 2015)	$f_t = 0.56(f_c')^{0.5}$
CEB-FIP (Müller and Hilsdorf, 1990)	$f_t = 0.3(f_c')^{0.67}$
Choi and Yuan (Choi and Yuan, 2005)	$f_t = 0.6(f_c')^{0.5}$
Xu and Shi (Xu and Shi, 2009)	$f_t = 0.21(f_c')^{0.83}$
Perumal (Perumal, 2015)	$f_t = 0.188(f_c')^{0.84}$
Al-Baghdadi (1) (Al-Baghdadi et al., 2021)	$f_t = 0.015(f_c')^{1.531}$
Al-Baghdadi (2)	$f_t = 0.022(f_c')^{1.428}$
Flexural Strength and Tensile Strength Relations	
Xu and Shi (Xu and Shi, 2009)	$f_t = 1.741(f_f)^{0.879}$
Perumal (Perumal, 2015)	$f_t = 1.63(f_f)^{0.89}$
Al-Baghdadi (1) (Al-Baghdadi et al., 2021)	$f_t = 0.696(f_f)^{1.032}$
Al-Baghdadi (2)	$f_t = 0.632(f_f)^{1.104}$
Compressive Strength and Flexural Strength Relations	
ACI 318 (American Concrete Institute, 2015)	$f_f = 0.62(f_c')^{0.5}$
Ahmed and Shah (Shah and Ahmad, 1985)	$f_f = 0.44(f_c')^{0.44}$
Xu and Shi (Xu and Shi, 2009)	$f_f = 0.39(f_c')^{0.39}$
Perumal (Perumal, 2015)	$f_f = 0.259(f_c')^{0.843}$
Al-Baghdadi (1) (Al-Baghdadi et al., 2021)	$f_f = 0.025(f_c')^{1.470}$
Al-Baghdadi (2)	$f_f = 0.056(f_c')^{1.229}$

In Figure 12, the correlation between compressive and split tensile strength was conducted using regression. From the figure, the empirical relationship between two fiber types is listed in Table 8. For the 0.5 mm diameters and 1 mm fiber diameters, coefficient of determination (R^2) were found to be 0.95 and 0.96 respectively showing a substantial correlation. The experimental data were mostly resembling Xu and Shi (2009) and Perumal (2015). This paper's proposed equations are presented in Table 8–Table 10.

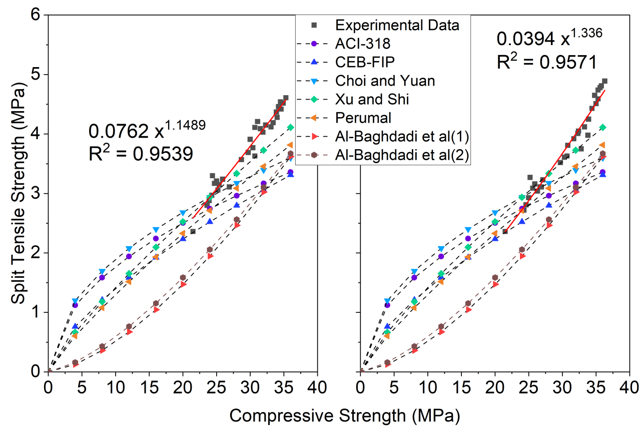

Figure 12. Relation between the compressive strength and splitting tensile strength of 0.5 mm (left) and 1 mm (right).

Table 8. Proposed equations for compressive vs. splitting tensile strength

Fiber type	Equations
0.5 mm steel diameters	$f_t = 0.072(f_c')^{1.1489}$
1 mm steel diameters	$f_t = 0.0394(f_c')^{1.336}$

Same analysis was done to determine the relationship between Flexural strength and split tensile strength. For the regression analysis, R^2 was found to be 0.97 for both cases. In these cases the values were closely related to Al-Baghdadi et al. (2021) works.

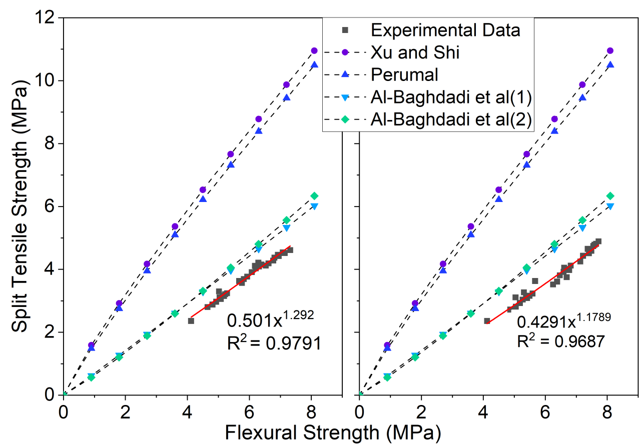

Figure 13. Relation between the flexural strength and splitting tensile strength of 0.5 mm (left) and 1 mm (right).

Table 9. Proposed equations for flexural vs. splitting tensile strength

Fiber type	Equations
0.5 mm steel diameters	$f_f = 0.501(f_f)^{1.292}$
1 mm steel diameters	$f_f = 0.4291(f_f)^{1.1789}$

Finally, the regression assessment was carried out for compressive strength and flexural strength.

The results showed a significant relationship between them as R^2 values were 0.97 and 0.96 respectively. Data was closely correlated and matched with data of Perumal (2015).

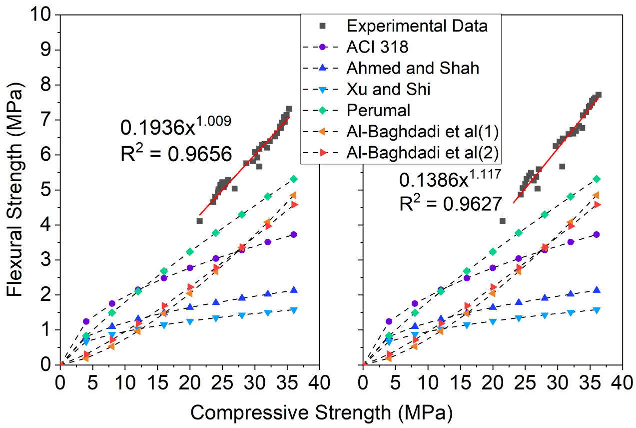

Figure 14. Relation between the compressive strength and flexural strength of 0.5 mm (left) and 1 mm (right).

Table 10. Proposed equations for flexural vs. splitting tensile strength

Fiber type	Equations
0.5 mm steel diameters	$f_f = 0.501(f'_c)^{1.292}$
1 mm steel diameters	$f_f = 0.4291(f'_c)^{1.1789}$

4 CONCLUSION

The findings of the study undertaken on different Steel Fiber-Reinforced Concrete (SFRC) mixtures for curing periods up to 28 days have been presented in the previous chapters. Based on the limited number of variables examined, the following conclusions are drawn:

a) In comparison to specimens without steel fibers, the compressive strength of concrete containing 1%, 1.5%, and 2% steel fibers is higher. Relative to the control sample, the compressive strength increases by approximately 18% with the inclusion of steel fibers.
b) SFRC with 1.5% fiber content shows higher values in all strength parameters—cube compressive strength, split tensile strength, and beam flexural strength—compared to the control specimen (0% fiber content).
c) Considering aspect ratios, specimens with an aspect ratio of 70 exhibit higher strength properties compared to those with aspect ratios of 50 and 60.
d) The flexural strength of SFRC increases by approximately 36% with the addition of steel fibers compared to the control sample.
e) The concrete cube split tensile strength increases by about 35% with the inclusion of steel fibers.
f) SFRC containing 1.5% steel fiber with an aspect ratio of 70 is found to be the most effective in terms of strength development.
g) The results of this study are consistent with several previous research findings.
h) The proposed empirical equations not only provide retrospective validation but also establish a framework for predictive modeling of fiber-reinforced concrete behavior under varying fiber dosages and aspect ratios. These equations can be integrated into computational frameworks or parametric design tools to simulate performance under different loading and environmental conditions.

DISCLAIMER

The authors declare no conflict of interest.

REFERENCES

Al-Baghdadi, H. M., Al-Merib, F. H., Ibrahim, A. A., Hassan, R. F. and Hussein, H. H. (2021), 'Effects of coarse aggregate maximum size on synthetic/steel fiber reinforced concrete performance with different fiber parameters', *Buildings* **11**(4), 158.
URL: *https://doi.org/10.3390/buildings11040158*

American Concrete Institute (2009), *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI PRC-211.1-91)*, American Concrete Institute.

American Concrete Institute (2015), *Building Code Requirements for Structural Concrete (ACI 318M-14): An ACI Standard: Commentary on Building Code Requirements for Structural Concrete (ACI 318M-14)*, American Concrete Institute, Farmington Hills, MI.

American Concrete Institute (2018), *Guide to Design with Fiber-Reinforced Concrete*, American Concrete Institute, Farmington Hills, Michigan.

ASTM A01 Committee (2022), 'Specification for steel fibers for fiber-reinforced concrete'.
URL: *https://doi.org/10.1520/A0820_A0820M-22*

ASTM C01 Committee (2022), 'Specification for portland cement'.
URL: *https://doi.org/10.1520/C0150_C0150M-22*

Barros, J. A. O. and Figueiras, J. A. (1999), 'Flexural behavior of sfrc: Testing and modeling', *Journal of Materials in Civil Engineering* **11**(4), 331–339.
URL: *https://doi.org/10.1061/(ASCE)0899-1561(1999)11:4(331)*

Bernard, E. S. and Pircher, M. (2000), Influence of geometry on performance of round determinate panels made with fibre reinforced concrete, Technical report, University of Western Sydney, Nepean, School of Civic Engineering.

Biswas, R. K., Bin Ahmed, F., Haque, M. E., Provasha, A. A., Hasan, Z., Hayat, F. and Sen, D. (2021), 'Effects of steel fiber percentage and aspect ratios on fresh and hardened properties of ultra-high performance fiber reinforced concrete', *Applied Mechanics* **2**(3), 501–515.
URL: *https://doi.org/10.3390/applmech2030028*

British Standards Institution (1983), *Testing Concrete*, British Standards Institution, London.

Bureau of Indian Standards (1999), 'Is 5816 (1999): Method of test splitting tensile strength of concrete'.

Choi, W.-C., Jung, K.-Y., Jang, S.-J. and Yun, H.-D. (2019), 'The influence of steel fiber tensile strengths and aspect ratios on the fracture properties of high-strength concrete', *Materials* **12**(13), 2105.
URL: *https://doi.org/10.3390/ma12132105*

Choi, Y. and Yuan, R. L. (2005), 'Experimental relationship between splitting tensile strength and compressive strength of gfrc and pfrc', *Cement and Concrete Research* **35**(8), 1587–1591.
URL: *https://doi.org/10.1016/j.cemconres.2004.09.010*

Ganapathy, G. P., Keshav, L., Ravindiran, G. and Razack, N. A. (2022), 'Strength prediction of self-consolidating concrete containing steel fibre with different fibre aspect ratio', *Journal of Nanomaterials* **2022**, 7604383.
URL: *https://doi.org/10.1155/2022/7604383*

Gao, J., Sun, W. and Morino, K. (1997), 'Mechanical properties of steel fiber-reinforced high-strength lightweight concrete', *Cement and Concrete Composites* **19**(4), 307–313.
URL: *https://doi.org/10.1016/S0958-9465(97)00023-1*

Garcia-Taengua, E., Bakhshi, M. and Ferrara, L. (2021), 'Meta-analysis of steel fiber-reinforced concrete mixtures leads to practical mix design methodology', *Materials* **14**(14), 3900.
URL: *https://doi.org/10.3390/ma14143900*

Hillerborg, A. (1980), 'Analysis of fracture by means of the fictitious crack model, particularly for fibre reinforced concrete'. Available online.

Iqbal Khan, M. and Abbas, Y. M. (2023), 'Significance of fiber characteristics on the mechanical properties of steel fiber-reinforced high-strength concrete at different water-cement ratios', *Construction and Building Materials* **408**, 133742.
URL: *https://doi.org/10.1016/j.conbuildmat.2023.133742*

Khamees, S. S., Kadhum, M. M. and Alwash, N. A. (2020), 'Effects of steel fibers geometry on the mechanical properties of sifcon concrete', *Civil Engineering Journal* **6**(1), 21–33.
URL: *https://doi.org/10.28991/cej-2020-03091450*

Kim, D.-J., Kim, S.-H. and Choi, W.-C. (2021), 'Characteristics of restrained drying shrinkage on arched steel fiber-reinforced concrete', *Applied Sciences* **11**(16), 7537.
URL: *https://doi.org/10.3390/app11167537*

Liang, Z., Peng, X. and Wang, H. (2023), 'The influence of aspect ratio of steel fibers on the conductive and mechanical properties of compound cement reactive powder concrete', *Coatings* **13**(2), 331.
URL: *https://doi.org/10.3390/coatings13020331*

Lim, T. Y., Paramasivam, P. and Lee, S. L. (1987), 'Analytical model for tensile behavior of steel-fiber concrete', *ACI Materials Journal* **84**(4), 286–298.
URL: *https://doi.org/10.14359/1454*

Mahadik, S. A., Kamane, S. K. and Lande, A. C. (2014), 'Effect of steel fibers on compressive and flexural strength of concrete', *International Journal of Advanced Structures and Geotechnical Engineering* **3**(4), 388–392.

Mir, M. S. (2013), 'Laboratory characterisation of steel fiber reinforced concrete for varying fiber proportion and aspect ratio'. Available at: https://www.academia.edu/97137733/Laboratory_Characterisation_of_Steel_Fiber_Reinforced_Concrete_for_varying_Fiber_Proportion_and_Aspect_Ratio (Accessed 7 June 2025).

Müller, H. S. and Hilsdorf, H. K. (1990), Evaluation of the time dependent behavior of concrete: Summary report on the work of general task group 9, Technical report, Comité Euro-International du Béton (CEB), Lausanne. Bulletin d'information / CEB.

Naaman, A. E. (2018), Fiber reinforced concrete: Five decades of progress, *in* 'Proceedings of the 4th Brazilian Conference on Composite Materials', Pontifícia Universidade Católica do Rio de Janeiro, pp. 35–56.

Neeraja, D. (2013), 'Experimental investigations on strength characteristics of steel fibre reinforced concrete', *International Journal of Scientific & Engineering Research* **4**(2), 1–6.

Ni, K., Shi, Y. X., Ding, Y. N., Zhang, Y. G., Shi, J. B. and Liu, W. (2014), 'Influence of aspect ratio of hooked end steel fiber on flexural behavior of fiber reinforced concrete', *Key Engineering Materials* **629–630**, 560–564.

Ou, Y.-C., Tsai, M.-S., Liu, K.-Y. and Chang, K.-C. (2012), 'Compressive behavior of steel-fiber-reinforced concrete with a high reinforcing index', *Journal of Materials in Civil Engineering* **24**(2), 207–215.

Perumal, R. (2015), 'Correlation of compressive strength and other engineering properties of high-performance steel fiber–reinforced concrete', *Journal of Materials in Civil Engineering* **27**(1), 04014114.

Rana, A. (2013), 'Some studies on steel fiber reinforced concrete', *International Journal of Emerging Technology and Advanced Engineering* **3**(1), 120–127.

Romualdi, J. P. and Batson, G. B. (1963), 'Mechanics of crack arrest in concrete', *Journal of the Engineering Mechanics Division* **89**(3), 147–168.

Sable, K. S. and Rathi, M. K. (2012), 'Effect of different type of steel fibre and aspect ratio on mechanical properties of self compacted concrete', *IJEIT–International Journal of Engineering and Innovative Technology* **2**(1), 184–188.

Shah, S. P. and Ahmad, S. H. (1985), 'Structural properties of high strength concrete and its implications for precast prestressed concrete', *PCI Journal* **30**(6), 92–119.

Shende, A. and Pande, A. (2012), 'Comparative study on steel fiber reinforced cum control concrete under tension', *Open Journal of Civil Engineering* pp. 61–66.

Shetty, M. S. (2021), *Concrete Technology: Theory and Practice*, S Chand and Company Limited, New Delhi.

Sivanantham, P. A., Prabhu, G. G., Vimal Arokiaraj, G. G. and Sunil, K. (2022), 'Effect of fibre aspect-ratio on the fresh and strength properties of steel fibre reinforced self-compacting concrete', *Advances in Materials Science and Engineering* **2022**, 1–8.

Soranakom, C., Yekani-Fard, M. and Mobasher, B. (2008), Development of design guidelines for strain softening fiber reinforced concrete, *in* '7th RILEM International Symposium on Fibre Reinforced Concrete', pp. 513–523. Available at: https://www.academia.edu/download/31150824/Soranakom_yekanifard_mobasher_Befib2008_final.pdf (Accessed 7 June 2025).

Swamy, R. N. and Mangat, P. S. (1974), 'A theory for the flexural strength of steel fiber reinforced concrete', *Cement and Concrete Research* **4**(2), 313–325.

Vairagade, V. S. and Kene, K. S. (2013), 'Strength of normal concrete using metallic and synthetic fibers', *Procedia Engineering* **51**, 132–140.

Veeramanikandan, K., Thiagarajan, K. and Maluvu, S. (2023), 'Experimental investigation on crimped steel fiber in m30 concrete with treated rubber powder as partial replacement of fine aggregate', *International Journal of Scientific Research in Engineering and Management* **10**(9).

Xu, B. W. and Shi, H. S. (2009), 'Correlations among mechanical properties of steel fiber reinforced concrete', *Construction and Building Materials* **23**(12), 3468–3474.

Xu, L., Wang, J., Hu, X., Ran, B., Wu, T., Zhou, X. and Xiong, Y. (2024), 'Physical performance, durability, and carbon emissions of recycled cement concrete and fully recycled concrete', *Construction and Building Materials* **447**, 138128.

Yusuf, M. S., Isak, A. B., Mohamud, G. A., Warsame, A. H., Osman, Y. I., Ibrahim, A. H. and Elmi, L. A. A. (2023), 'Effect of steel fiber on concrete's compressive strength', *Open Journal of Civil Engineering* **13**(1), 192–197.

Zhao, L., Chen, G. and Huang, C. (2023), 'Experimental investigation on the flexural behavior of concrete reinforced by various types of steel fibers', *Frontiers in Materials* **10**, 1301647.

Zheng, Y., Lv, X., Hu, S., Zhuo, J., Wan, C. and Liu, J. (2024), 'Mechanical properties and durability of steel fiber reinforced concrete: A review', *Journal of Building Engineering* **82**, 108025.