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ARTICLE

# Mechanical Performance of Fiber-Reinforced Self-Compacting Concrete: Comparative Analysis and Structural Implications

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## ABSTRACT

The aim of this study is to assess the mechanical properties of different types of fibre-reinforced self-compacting concrete (FRSCC) such as steel fibre (SFSCC), glass fibre (GFSCC), polypropylene fibre (PFSCC) and plain self-compacting concrete (SCC). This will involve the evaluation of various fibres' influences on the key strength parameters including compressive, split tensile, flexural and shear strengths. The results obtained from the compressive strength tests show that SFSCC has the best performance among all fibre-reinforced mixes with a peak value of 40.41 MPa at 0.5% fibre dosage. In relation to split tensile strength, SFSCC has a slight increase over plain SCC while GFSCC and PFSCC have shown significant improvements with increasing fibre content. All three types of FRSCCs indicate an enhancement in flexural strength, with SFSCC having higher values than any other type. Shear strength tests also confirm that SFSCC is superior to both GFSCCs and PFSCCs as well as the control mix. From these findings it is clear that the incorporation of fibres into SCC significantly improves its mechanical properties whereby steel fibres provide the most pronounced overall benefits. Each fibre type contributes differently depending on the mechanical parameter being analysed which implies there are possibilities for customised applications based on specific structural requirements. The findings of this study have shown that fibre reinforcement can improve the performance of SCC for future construction needs. Future research should focus on optimising fibre dosages, exploring hybrid fibre combinations and assessing long-term durability to increase the use of FRSCC in modern structural engineering practices.

***Keywords:*** Fiber-Reinforced Concrete; Self-Compacting Concrete; Steel Fiber; Glass Fiber; Polypropylene Fiber; Mechanical Properties

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# 1. Introduction

A key factor in the behavior of steel fiber reinforced concrete (SFRC) is its mix design, which requires precise ratios between the various components [1]. The composition and dosage of constituents, such as fibers and the cementitious matrix, determine the composite's mechanical and physical qualities [2, 3]. Adding steel fibers significantly alters the composite's behavior, particularly during cracking, as the matrix must be mechanically strong to transfer stresses to the fibers [4]. The right mix component selection, dosage, and synergistic effects greatly impact SFRC efficacy. The mechanical behavior of concrete is directly influenced by the characteristics of the cementitious matrix and aggregates [5]. Uniform elasticity and abrupt failure occur when the coarse aggregate's elastic modulus matches that of the matrix, while differences in elastic moduli lead to microcracking and softening of the stress-strain curve [6, 7]. Although steel fibers enhance strength and ductility, they can reduce workability, which can be mitigated by increasing fine aggregate content or adding fluidizing chemicals [8]. Additionally, the water-to-cement ratio and the mechanical strength of cured concrete are influenced by the minimum cement dose, based on the maximum coarse aggregate size [9, 10]. Understanding and controlling these factors is essential to optimize SFRC performance, balancing mechanical behavior and workability to ensure the composite's overall efficacy [11].

The study examined various volume fractions and fiber lengths in steel-fiber-reinforced concrete to contribute to the ongoing research on composite materials [12,13]. Concrete specimens with steel fibers at volume fractions of 1% and 2% underwent three experimental tests: four-point bending tests on notched specimens to measure initial fracture strength and ductility, uniaxial compression tests to ascertain compressive strength, and direct tensile testing to assess ultimate tensile strain and strength [14–16]. The results demonstrated that while the addition of fibers significantly altered post-cracking behavior, it did not affect compressive strength [17, 18]. Notably, specimens with longer fibers exhibited increased ductility, evidenced by a larger area under the curves in the four-point bending tests [19, 20]. In the presence of fibers, direct tensile testing indicated a higher ultimate strain but a lower maximum strength [21, 22]. The latter part of this work investigates the tensile strength of steel fiber reinforced concrete (SFRC) using both theoretical and experimental methods [23, 24]. An analytical model of SFRC was created based on the theoretical foundation provided in the research, determining upper and lower bounds for SFRC tensile stiffness and strength through homogenization methods and variational principles [25, 26]. AI-assisted models have demonstrated high diagnostic accuracy in pathology, with near 100% sensitivity and robust generalizability across institutions [27]. Similarly, in material science, machine learning models have achieved $R^2 > 0.9$ for real-time prediction of water penetration and sorptivity in cementitious systems, offering a scalable tool for automated durability assessment [28].

The research aimed to evaluate the enhancements in compressive strength achieved by Steel Fiber Reinforced Self-Compacting Concrete (SFSCC) compared to plain SCC and other fiber-reinforced variants. Additionally, it sought to assess the split tensile strength of hybrid fiber-reinforced SCC (HFSCC) and explore the improvements in flexural strength. Another key objective was to examine the shear strength enhancement provided by SFSCC in comparison to plain SCC, Glass Fiber Reinforced SCC (GFSCC), and Polypropylene Fiber Reinforced SCC (PFSCC).

# 2. Experimental Programme

This investigation examines the shear strength characteristics and deformation parameters of self-compacting concrete (SCC). The experimental setup designed to meet the objectives. It discusses the properties of the materials used in the concrete mixtures employed in the experiments, along with the specific composition of the SCC. Additionally, the testing procedures used to verify the self-compacting properties of various combinations of materials are explained.

## 2.1. Materials

The concrete test specimens were created using a mix of cement, fiber, fly ash, fine aggregate (coarse sand), coarse aggregate, water, superplasticizer, viscosity-modifying admixtures, and steel. The composition of these materials adhered to the specifications outlined in the relevant Indian Standards.

**Cement**: For the duration of the study, Portland Pozzolana Cement 43 Grade (PPC 43 Grade) was utilized, sourced from a single supplier. This cement adhered to the standards set by IS: 1489 (Part-I): 1991 for all mixtures. The physical properties of the cement met the requirements specified by the Indian Standard IS 10262.

**Fly Ash**: The fly ash utilized in the experiments originated from the RattanIndia Power Limited (RPL) thermal power plant in Amravati, India and underwent sieving through a 90-micron sieve to meet Indian Standard IS-3812 [BIS, 2013] specifications. It exhibited a specific gravity of 2.2 and a specific surface area of 450 $m^2/g$, indicating its particle size and reactivity. The fly ash composition included a silica content of 63.99%, with silica, alumina, and iron oxide collectively constituting 92.7% of its composition. It had a pH value of 10 and a loss on ignition of 2.12%, factors that influence its chemical properties and behavior in concrete mixtures. These characteristics highlight the suitability of the fly ash from Ramagundam thermal power station for enhancing concrete performance while adhering to established quality standards.

**Fine aggregate**: Characteristics highlighted in **Table 1** are the suitability of the sand for use in construction applications, ensuring it meets required standards for particle size distribution and physical properties in concrete mixes.

**Table 1.** Physical properties of fine aggregate.

| Property | Value |
|---|---|
| Type of Aggregate | Fine Aggregate |
| Compliance Standard | Zone-II (Indian Standard 383) |
| Source | Nearby River |
| Specific Gravity | 2.65 |
| Bulk Density | 1.45 $g/cm^3$ |

**Coarse Aggregate:** For the coarse aggregates, Characteristics highlighted in **Table 2**.

**Table 2.** Physical properties of coarse aggregate.

| Property | Value |
|---|---|
| Type of Aggregate | Coarse Aggregate |
| Source | Locally Sourced Crushed Stone |
| Nominal Maximum Size | 12.5 mm |
| Compliance Standard | IS-383 (Indian Standard) |
| Specific Gravity | 2.58 |
| Bulk Density | 1.65 $g/cm^3$ |
| Particle Distribution | 70% > 10 mm, 30% < 10 mm |

**Water:** For both the mixing and curing processes of the concrete specimens, clean tap water free of harmful substances was utilized.

**Superplasticizer:** In the concrete mix, Glenium51, a commercially available superplasticizer, was utilized to achieve substantial water reduction while maintaining workability and enhancing performance. Glenium51 is classified as a high-performance additive based on modified polycarboxylic ether, meeting the stringent standards of ASTM C494 Types A and F, as well as IS 9103:1999. This superplasticizer is characterized by a specific gravity of 1.1, indicating its relative density compared to water. Its molecular structure facilitates rapid adsorption onto cement particles, facilitating their dispersion throughout the mixture and effectively increasing the reactive surface area of cement grains upon hydration. This process enhances the overall fluidity of the concrete mixture without compromising its strength or durability, making it ideal for applications where high-performance and improved workability are desired.

**Fibers**:

**(a)steel fibers** - The steel fibers used in the study conform to Indian Standards IS-1786 [BIS, 2008]. These fibers have a crimped shape with a nominal diameter of 0.5 mm and a cut length of 30mm, resulting in an aspect ratio of 60. They possess a tensile strength of 850 MPa and a modulus of elasticity of $2.1 \times 10^5$ MPa. These characteristics make the steel fibers suitable for reinforcing concrete, enhancing its structural integrity and durability. **Figure 1** shows the steel fibers

**Figure 1.** Steel fibers.

**(b) Glass fibers:** specifically Anti-Crack HD, are engineered to resist alkali in concrete and mortar applications, aiming to minimize plastic shrinkage cracking. These fibers are monofilament in design with a diameter of 14 microns and a specific gravity of 2.68. They typically appear clear or white in color and have a low moisture content of less than 0.6% as per ISO 3344 standards. Glass fibers exhibit a modulus of elasticity of 72 GPa and possess a high tensile strength of 1,700 MPa.

**(c) Polypropylene fibers**: Fibers used in the study were approximately 32.57 mm long with a diameter of 1153.29 µm and an average circumference of 539.287 µm. These fibers exhibited a tensile strength of approximately 525 MPa, a modulus of elasticity of about 7.55 GPa, and a Poisson ratio of around 0.2. **Table 3** provides physical properties of steel fibers.

**Table 3,** Physical properties of steel fibers.

| Fiber Type | Property | Value |
|---|---|---|
| **Steel Fibers** | Compliance Standard | IS-1786 [BIS, 2008] |
| | Shape | Crimped |
| | Nominal Diameter | 0.5 mm |
| | Cut Length | 30 mm |
| | Aspect Ratio | 60 |
| | Tensile Strength | 850 MPa |
| | Modulus of Elasticity | $2.1 \times 10^5$ MPa |
| | Manufacturer | Stewols India Pvt. Ltd., Nagpur |
| | Source of Procurement | Mcon Construction Supplier, Amravati |
| **Glass Fibers** | Type | Anti-Crack HD |
| | Compliance Standard | ISO 3344 |
| | Shape | Monofilament |
| | Diameter | 14 microns |
| | Specific Gravity | 2.68 |
| | Moisture Content | <0.6% |
| | Modulus of Elasticity | 72 GPa |
| | Tensile Strength | 1,700 MPa |
| | Manufacturer | Owens Corning |
| | Type of Glass | E-glass |
| | Source of Procurement | Mcon Construction Supplier, Amravati |
| **Polypropylene Fibers** | Length | 32.57 mm |
| | Diameter | 1153.29 µm |
| | Circumference | 539.287 µm |
| | Tensile Strength | 525 MPa |
| | Modulus of Elasticity | 7.55 GPa |
| | Poisson Ratio | 0.2 |
| | Manufacturer | Stewols India Pvt. Ltd., Nagpur |
| | Source of Procurement | Mcon Construction Supplier, Amravati |

## 2.2. SCC Mix Proportions and Properties

Two Self-Compacting Concrete (SCC) mixtures of M30 grade, each with a different fibre factor (calculated as the product of the fibre's aspect ratio and capacity) and a 28-day cylinder strength of 30 MPa, were utilized in this study. The initial proportioning of these mixes was carried out using the ACI (American Concrete Institute) mix design method. Following this, the mixture proportions were finely tuned through a series of trial mixes to achieve the desired fresh properties characteristic of SCC. To ensure the self-compacting nature of the concrete, a significant amount of fine materials was incorporated to maintain stability, while a high dosage of superplasticizers was used to achieve the necessary flowability. This combination was essential to attain the optimal balance of stability and workability required for effective self-compacting concrete.

The **Table 4** outlines the mix proportions for SCC of grade M30, specifying the quantities of various ingredients per cubic meter of concrete. For the M30 mix, it includes 345 kilograms of cement, 319 kilograms of fly ash, 735 kilograms of coarse aggregates (CA), 931 kilograms of fine aggregates (FA), and 200 kilograms of water. The water-to-binder ratio (w/b) is set at 0.3, which indicates a relatively low amount of water compared to the total binder content (cement + fly ash). Additionally, 6 kilograms per cubic meter of superplasticizer (SP) is used to improve the workability and flowability of the concrete mixture without compromising its strength. This mix design is tailored to achieve the desired strength and performance characteristics of SCC grade M30, ensuring it meets the required standards for construction applications.

The **Table 5** summarizes the number of concrete specimens (cubes, cylinders) prepared with different dosages of steel, glass, and polypropylene fibers, measured as a percentage by volume of concrete. For each type of fiber, specimens were made at fiber dosages of 0%, 0.25%, 0.5%, 0.75%, and 1%. Each dosage level includes 6 cubes, and 3 cylinders, totaling 30 cubes, and 15 cylinders per fiber type. This setup ensures a comprehensive analysis of the mechanical properties across varying fiber concentrations for each type of fiber reinforcement.

The **Table 6** summarizes the fresh state workability properties of SCC MIX M30 with varying fiber dosages (0%, 0.25%, 0.5%, 0.75%, 1%). As fiber content increases, the concrete's slump decreases from 739 mm to 561 mm, indicating reduced flowability. Similarly, the time for concrete to flow through the V-Funnel and J-Ring increases with higher fiber dosages, reflecting decreased fluidity and passing ability through reinforcement congested areas. These results highlight the trade-off in SCC between adding fibers for improved mechanical properties and maintaining optimal workability. These tests were performed in accordance with EFNARC guidelines, and the results are summarized in **Table 6**. While there was a moderate increase in flow time and J-ring flow difference, the values remained within the acceptable limits for self-compacting concrete, albeit near the lower threshold at higher fibre contents. Therefore, we cautiously maintain that the mixes, even at 1% fibre dosage, still conform to SCC classification, though with a reduced margin of workability.

**Table 4.** Mix proportions of SCC.

| Mix | Cement (kg/cum) | FlyAsh (kg/cum) | CA (kg/cum) | FA (kg/cum) | water (kg/cum) | w/b | SP (kg/ cum) |
|---|---|---|---|---|---|---|---|
| M30 | 345 | 319 | 735 | 931 | 200 | 0.3 | 6 |

**Table 5.** Total specimen prepared for FRSCC.

| Dosage of Fibers (% by Volume of Concrete) | Steel Fibers | | | Glass Fibers | | | Polypropylene Fibers | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cubes | L-Shaped Cubes | Cylinders | Cubes | L-Shaped Cubes | Cylinders | Cubes | L-Shaped Cubes | Cylinders |
| 0 | 6 | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 3 |
| 0.25 | 6 | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 3 |
| 5 | 6 | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 3 |
| 0.75 | 6 | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 3 |
| 1 | 6 | 3 | 3 | 6 | 3 | 3 | 6 | 3 | 3 |
| Total | 30 | 15 | 15 | 30 | 15 | 15 | 30 | 15 | 15 |

**Table 6.** The fresh state workability properties of SCC mixtures for MIX M30.

| Dosage of Fibers (%) | 0 | 0.25 | 0.5 | 0.75 | 1 |
|---|---|---|---|---|---|
| Slump Test (mm) | 739 | 690 | 670 | 591 | 561 |
| T50 Slump flo (s) | 3 | 5 | 5 | 7 | 8 |
| V funnel (s) | 6 | 7 | 8 | 16 | 19 |
| V funnel @ T5 min (s) | 6 | 7 | 9 | 20 | 23 |
| J-ring | 3 | 8 | 8 | 12 | 13 |

### 2.3. Shear Strength Testing

There are several methods available for evaluating the shear strength of concrete; however, many of these methods have practical limitations. These approaches often involve testing specimens with two potential shear planes, but it is rare for both planes to fail simultaneously during testing, which complicates achieving a pure shear condition. To address this challenge, shear tests were conducted using a method recommended by Ref. [25], which applies a pure shear force to the specimen. This method has been widely adopted by researchers investigating the shear behavior of concrete [26]. The specimen used is L-shaped, formed by placing a wooden block measuring 150 × 90 × 60 mm into a 150 mm cube mold. The steel plates are positioned on top of the L-shaped specimen, with the 150 × 85 × 10 mm plate resting on the side adjacent to the solid portion of the block (150 × 150 × 90 mm). The 22 mm diameter bar is placed alongside this plate, while the 12 mm diameter bar rests on the lower plate. The second steel plate, measuring 150 × 110 × 10 mm, is then placed on top of the two bars to complete the setup. The test can be performed using a compression testing machine and requires two mild steel plates (150 × 85 × 10 mm and 150 × 110 ×10 mm) and two bars (12 mm and 22 mm in diameter).

## 3. Results and Discussions

This section delves into the findings and outcomes from the examinations conducted on various specimens. The research project on the mechanical properties of FRSCC is structured into distinct phases. The initial phase focuses on optimizing the quantity of steel fibers, glass fibers & Polypropylene fibers added to concrete, varying from 0% to 1% by volume, across different concrete grades. This phase aims to investigate the effects of varying fiber content on the properties of SCC.

The **Figure 2** compares compressive strengths (in MPa) of different types of fiber-reinforced self-compacting concrete. Plain SCC starts at 39.07 MPa without fibers and decreases slightly with increasing fiber dosage up to 1%. SFSCC consistently shows the highest strength improvement, reaching 40.41 MPa at 0.5% fiber. GFSCC and PFSCC also enhance strength, achieving 39.80 MPa and 39.21 MPa, respectively, at the same dosage. Overall, fiber reinforcement, especially steel and glass, boosts SCC's compressive strength compared to plain SCC across different fiber percentages.

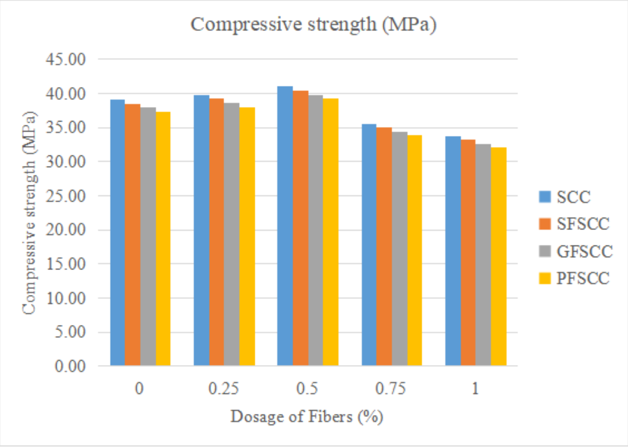


**Figure 2.** Compressive strength of concrete.

The split tensile strength is calculated using following formula:

$$f_{ct} = \frac{2P}{\pi L D}$$

Where,

- $f_{ct}$ = Split tensile strength (MPa)
- $P$ = Maximum applied load on the specimen (N)
- $L$ = Length of the cylindrical specimen (mm)
- $D$ = Diameter of the cylindrical specimen (mm)

The **Figure 3** shows that for SCC without fibers (0% dosage), the split tensile strength starts at 3.61 MPa and gradually increases as fiber dosage increases. SFSCC consistently shows slightly lower split tensile strength values compared to SCC across all dosage levels, indicating a marginal trade-off in tensile strength for the benefits of steel fiber reinforcement. GFSCC and PFSCC demonstrate similar trends, with increasing fiber dosage correlating with higher split tensile strengths, though typically slightly lower than those of SCC without fibers. Overall, the table highlights how the addition of fibers—whether steel, glass, or polypropylene—affects the split tensile strength of self-compacting concrete mixes, influencing their mechanical properties and potential applications in construction for enhanced durability and performance under tension.

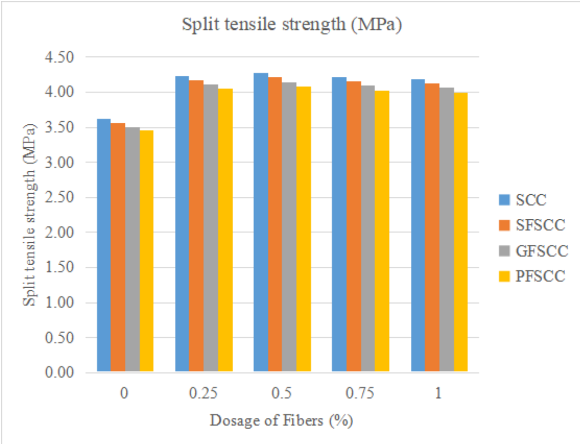


**Figure 3.** Split tensile strength (MPa).

The **Figure 4** shows that as the dosage of fibers increases from 0% to 1%, there is a noticeable enhancement in flexural strength across all types of SCC. For SCC without fibers, the flexural strength ranges from 3.92 MPa at 0% fiber dosage to 5.17 MPa at 1% dosage. Similarly, SFSCC, GFSCC, and PFSCC also demonstrate increased flexural strength with higher fiber dosages, showing improvements from initial strengths of 3.86 MPa, 3.81 MPa, and 3.75 MPa respectively at 0% dosage to 5.09 MPa, 5.02 MPa, and 4.94 MPa respectively at 1% dosage.

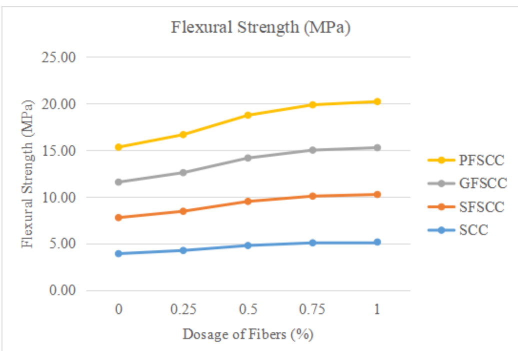


**Figure 4.** Flexural Strength (MPa).

These results highlight the effectiveness of fiber reinforcement in enhancing the flexural properties of SCC. Steel fibers generally provide the highest increase in flexural strength followed closely by glass fibers, while polypropylene fibers show slightly lower but still significant improvements. The data underscores the potential of fiber reinforcement to tailor SCC's mechanical properties to meet specific performance requirements in construction applications. As the fiber dosage increases, the percentage change in flexural strength (FS) becomes more pronounced. At 0% fiber content, the flexural strength of SCC is relatively low, but with each incremental increase in fiber dosage, the strength improves significantly. For example, at 1% fiber dosage, SCC shows an approximate 31.8% increase in flexural strength, from 3.92 MPa to 5.17 MPa. For SFSCC, the increase is about 32%, from 3.86 MPa to 5.09 MPa, while GFSCC and PFSCC show 31.8% and 31.5% increases respectively. These percentage changes further emphasize the influence of fiber type and dosage on the mechanical performance of SCC, with steel fibers contributing the most substantial improvements.

The **Figure 5** provides the compressive strength and flexural strength of various types of Self-Compacting Concrete with a fiber dosage of 0.5%. The concrete types evaluated include standard SCC, Steel Fiber Reinforced SCC, Glass Fiber Reinforced SCC, and Polypropylene Fiber Reinforced SCC. The recorded compressive strengths are 41.025 MPa for SCC, 40.410 MPa for SFSCC, 39.804 MPa for GFSCC, and 39.207 MPa for PFSCC. Correspondingly, the flexural strengths are 4.797 MPa for SCC, 4.780 MPa for SFSCC, 4.710 MPa for GFSCC, and 4.650 MPa for PFSCC. The data indicates a linear relationship between compressive strength (x) and flexural strength (y) for Hybrid Fiber Reinforced Self-Compacting Concrete (HFSCC), described by the equation $y = 0.1081x + 0.4117$, with a high correlation coefficient ($R^2 = 0.9984$). This strong positive correlation suggests that as the compressive strength increases, the flexural strength also increases. This relationship provides a predictive tool for estimating the flexural strength based on the compressive strength for FRSCC. The table highlights the variations in strength properties due to the addition of different fibers, while maintaining a consistent fiber dosage of 0.5%.

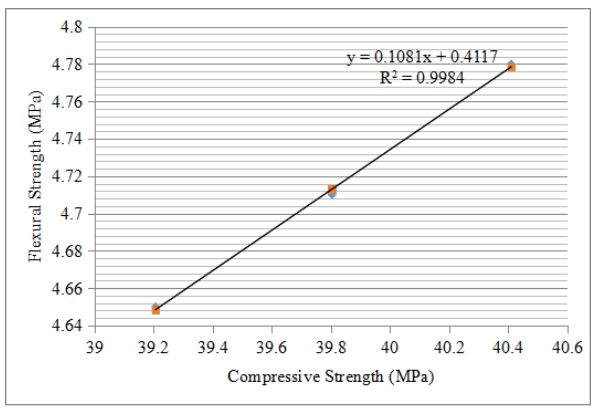


**Figure 5.** Relation of compressive strength and flexural strength for fiber-reinforced self-compacting concrete.

The **Figure 6** presents the compressive strength and split tensile strength of various types of Self-Compacting Concrete with a fiber dosage of 0.5%. The types of concrete evaluated include standard SCC, Steel (SFSCC), Glass (GFSCC), and Polypropylene (PFSCC). The compressive strengths recorded are 41.025 MPa for SCC, 40.410 MPa for SFSCC, 39.804 MPa for GFSCC, and 39.207 MPa for PFSCC. Correspondingly, the split tensile strengths are 4.275 MPa, 4.220 MPa, 4.200 MPa, and 4.150 MPa, respectively. Additionally, a linear relationship between compressive strength (x) and split tensile strength (y) for HFSCC is defined by the equation y = 0.0581x + 1.8767, with a high correlation coefficient ($R^2$ = 0.9403), indicating a strong positive correlation between the two strengths. This data underscores the minor variations in strength properties with different fiber reinforcements, while the linear relationship provides a predictive tool for estimating split tensile strength based on compressive strength for FRSCC.

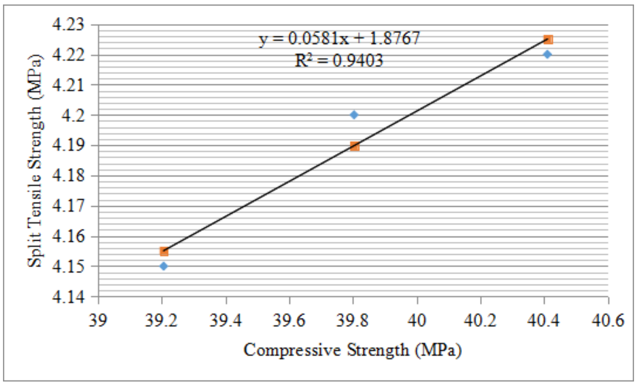


**Figure 6.** Relation of compressive strength and Split tensile strength for FRSCC.

## 3.1. Impact of Curing Duration on Shear Behavior

This study investigated the shear strength of specimens under room temperature conditions after curing periods of 7, 28, 60, and 90 days. The regular shear strength values at these time intervals were determined, along with their corresponding standard deviations. Shear stress at the cross-section was computed using the following formula:

$$\tau_u = \frac{P_u}{bd} \tag{1}$$

where:

- $\tau_u$ is the shear stress,
- $P_u$ is the maximum load at failure of the model,
- b and d are the measurements of the shear plane.

The shear strength is mentioned below **Figure 7**:

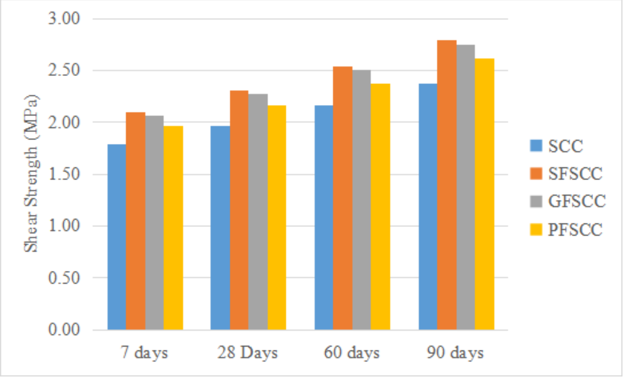


**Figure 7.** Shear Strength of FRSCC.

The **Figure 7** presents the shear strength (in MPa) of different types of fiber-reinforced self-SCC, including steel fiber (SFSCC), glass fiber (GFSCC), and polypropylene fiber (PFSCC), compared to plain SCC, with a fiber dosage of 0.25%, over curing periods of 7, 28, 60, and 90 days. For all types of concrete, shear strength increases with curing time. This indicates that the material's ability to resist shear forces improves as it continues to hydrate and cure. SFSCC exhibits the highest initial shear strength (2.10 MPa), followed closely by GFSCC (2.07 MPa) and then PFSCC (1.97 MPa). Plain SCC has the lowest initial shear strength (1.79 MPa). The inclusion of fibers significantly enhances the early-age shear strength of SCC. SFSCC continues to lead in shear strength (2.31 MPa), followed by GFSCC (2.28 MPa), PFSCC (2.16 MPa), and SCC (1.96 MPa). Fiber-reinforced concretes maintain a higher shear strength than plain SCC, demonstrating the effectiveness of fibers in improving structural performance.

The trend remains consistent, with SFSCC achieving the highest shear strength (2.54 MPa), followed by GFSCC (2.50 MPa), PFSCC (2.38 MPa), and SCC (2.16 MPa). The rate of increase in shear strength for fiber-reinforced concretes is slightly higher than for plain SCC, indicating ongoing benefits of fiber reinforcement over time. At 90 days, SFSCC still has the highest shear strength (2.80 MPa), GFSCC is slightly lower (2.75 MPa), followed by PFSCC (2.62 MPa), and SCC has the lowest (2.38 MPa). The continuous improvement in shear strength with curing time highlights the long-term advantages of using fibers in SCC.

Fibers enhance the shear strength of SCC by providing additional resistance to crack propagation and improving the composite action of the concrete. Steel fibers, in particular, offer superior performance due to their high tensile strength and stiffness, which contribute to higher shear strength values. The increase in shear strength over time is primarily due to the ongoing hydration process, which strengthens the concrete matrix. This effect is seen in both plain and fiber-reinforced SCC, although it is more pronounced in the latter due to the reinforcing action of the fibers. Steel fibers (SFSCC) are most effective in enhancing shear strength due to their mechanical properties, followed by glass fibers (GFSCC), which also provide significant improvements. Polypropylene fibers (PFSCC) contribute to shear strength enhancement but to a lesser extent compared to steel and glass fibers.

The **Figure 8** shows shear strength (MPa) of SCC and its fiber-reinforced variants steel SFSCC, glass GFSCC, and polypropylene PFSCC at different fiber dosages (0% to 1%). Shear strength increases with higher fiber dosages for all types. At 1% fiber dosage, SFSCC has the highest shear strength (3.43 MPa), followed by GFSCC (3.37 MPa) and PFSCC (3.21 MPa), with plain SCC having the lowest (2.91 MPa). Steel fibers provide the greatest enhancement in shear strength, followed by glass and polypropylene fibers. This highlights the significant role of fiber type and dosage in improving concrete's mechanical properties. The observed trend shows that adding fibers to SCC significantly increases shear strength, with higher dosages leading to greater improvements. Steel SFSCC provide the highest increase in shear strength, followed by glass GFSCC and polypropylene fibers PFSCC. This enhancement is due to fibers' ability to bridge cracks and distribute loads more effectively within the concrete matrix. The trend underscores the effectiveness of fiber reinforcement, particularly with steel fibers, in improving the structural performance of SCC.

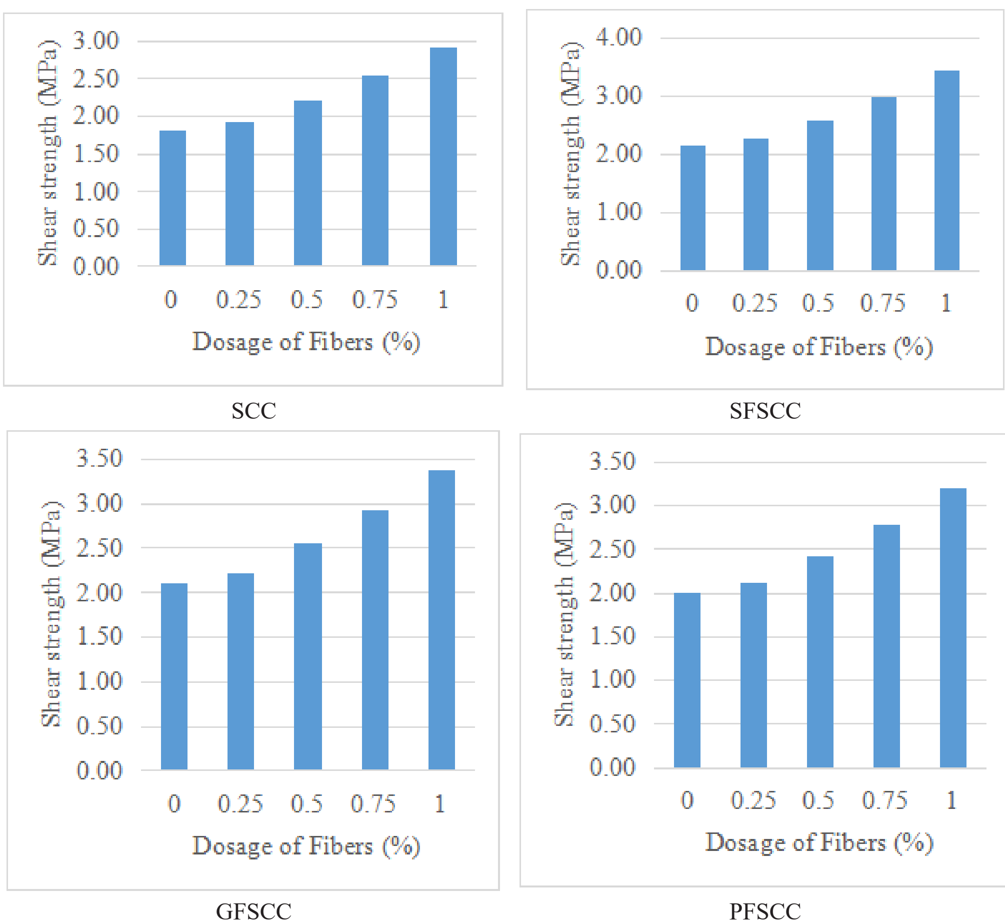


**Figure 8.** Variation of shear strength for the dosage of fibers.

## 3.2. Shear Strength in Fiber Reinforced Concrete

Several studies have investigated how fibers enhance the shear strength of steel fiber reinforced concrete, offering different theoretical models in published works [22, 25]. While these models are valuable, they have their limitations. Researchers have compared these models with experimental data to assess their reliability. According to the past work, the shear strength of fiber reinforced concrete (FRC) is determined by combining the inherent shear strength of the concrete matrix ($\tau_c$) with the additional shear strength Influence by the fibers ($\tau_f$). This relationship is formulated as:

$$\tau_u = \tau_c + \tau_f \tag{2}$$

In this context, $\tau_c$ denotes the shear strength of Self-compacting Concrete (SCC) without fibers, and its value $\tau_u$ was determined through experimental testing as reported in this work. The shear strength contributed by fibers ($\tau_f$) can be computed using the following equation:

$$\tau_f = \tau_u - \tau_c \tag{3}$$

**Table 7** presents a compilation of equations derived from various studies in the literature, which forecast the shear strength Influence by fibers. These equations commonly relate shear strength to the volume fraction of fibers, while also considering the aspect ratio of the fibers as an influencing factor.

**Table 7.** Summary of Former Studies on Shear Strength Influence by Fibers.

| Sr | Previous Study | $\tau_f$ |
|---|---|---|
| 1 | [10] | $1.3V_f^{0.896}$ |
| 2 | [6] | $4.0V_f^{0.9}$ |
| 3 | [21] | $4.23V_f$ |
| 4 | [25] | $2.45V_f$ |
| 5 | Present study | $1.8178V_f^{1.463}$ |

**Table 7** compares equations from various studies that quantify the shear strength contribution (τf) of fibers in concrete, all as a function of fiber volume fraction (Vf). Most studies show a near-linear relationship, with coefficients ranging from 1.3 to 4.23. The present study proposes a more complex non-linear relationship, indicating a more rapid increase in shear strength at higher fiber volumes. This highlights the variability in predicting fiber contributions to shear strength across different research approaches. The diversity in coefficients and exponents underscores the influence of different experimental conditions, fiber types, and concrete mixes used in these studies. Such variations emphasize the need for standardized testing methods to better understand and predict the role of fibers in enhancing concrete shear strength.

## 3.3. Failure Pattern

The failure of fiber-reinforced self-compacting concrete (SCC) specimens as per **Figure 9** can be attributed to multiple factors, including shear stress, fiber distribution, crack propagation mechanisms, and applied loading conditions. The presence of vertical cracks in several specimens indicates direct shear failure, where the applied stress exceeded the material's shear strength, leading to crack initiation and propagation. Additionally, fiber pull-out, particularly in recycled steel fiber (RSF) specimens, suggests that variations in fiber length resulted in inconsistent bonding with the cementitious matrix. Shorter RSF fibers failed to provide sufficient anchorage, allowing cracks to widen and fibers to dislodge prematurely. In contrast, fiber-reinforced SCC, with its uniform fiber length and better anchorage, enhanced crack resistance. Some specimens displayed severe crushing at the edges and near crack initiation points due to high stress concentrations, which exceeded the compressive strength of the concrete, leading to localized brittle failure. The presence of diagonal cracks in certain samples suggests mixed-mode failure, where both shear and tensile stresses contributed to crack propagation. This type of failure typically occurs when bending and shear forces act together, causing shear cracks to initiate at mid-depth and extend towards the edges. Furthermore, weak bonding at the fiber-matrix interface resulted in smooth fracture surfaces, indicating that inadequate fiber embedment or poor dispersion limited the fibers' ability to arrest crack growth. The failure analysis highlights that while fiber-reinforced SCC enhances performance by delaying crack propagation, its effectiveness depends on factors such as fiber length, distribution, and bonding quality. Proper mix design and fiber selection are essential to improving shear strength and ensuring better failure resistance in SCC.

**Figure 9.** Failure of concrete.

## 3.4. AI-Prediction Model

The AI model used in this graph is a Polynomial Regression Model (Degree 2) designed to predict the shear strength of different self-compacting concrete (SCC) variants over time. The model is trained using historical data points at 7, 28, 60, and 90 days and forecasts future shear strength values. The polynomial regression approach effectively captures the nonlinear trends in the strength development of SCC with different fiber reinforcements.

The **Figure 10** shows that the AI model uses Polynomial Regression (Degree 2) to predict the shear strength of different SCC variants over time. The graph shows actual strength values (solid markers) at 7, 28, 60, and 90 days and predicted trends (dashed lines) extending up to 120 days. SFSCC and GFSCC exhibit the highest strength gains, followed by PFSCC, while standard SCC shows a slower increase. The nonlinear trend highlights how strength gain slows with longer curing. Fiber reinforcement enhances shear strength compared to standard SCC. This AI-driven approach aids in forecasting concrete performance for optimized material selection and structural design.

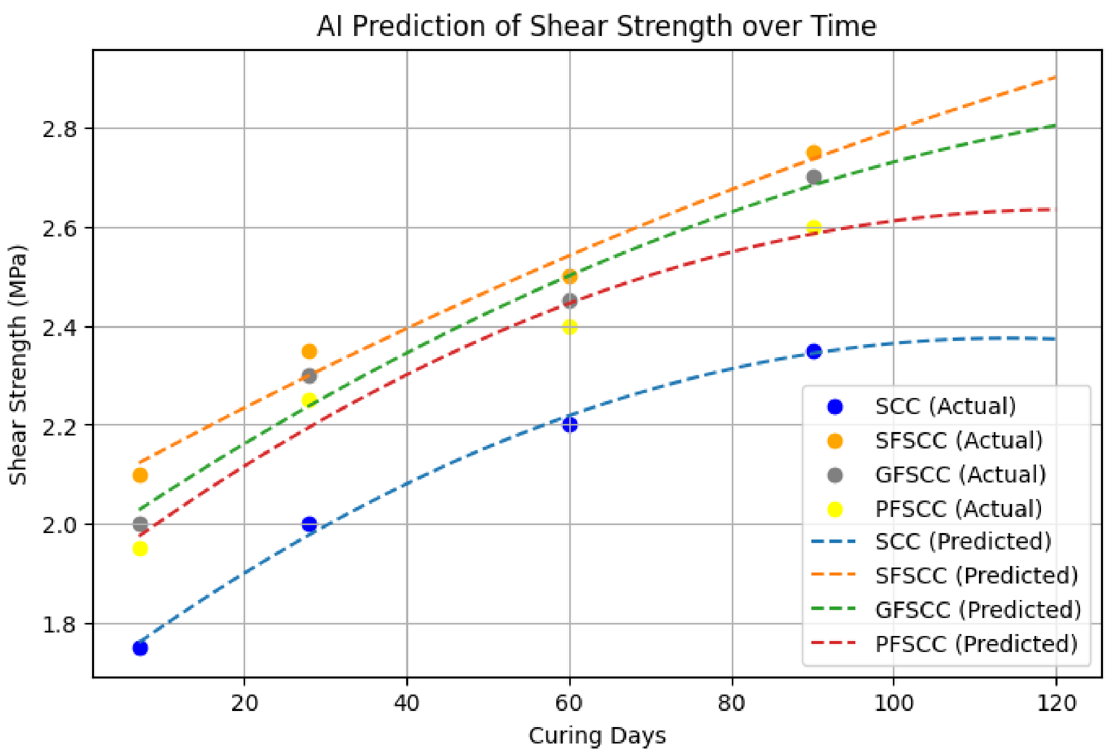


**Figure 10**. AI-Based Prediction of Shear Strength Growth in Self-Compacting Concrete Over Time.

# 4. Conclusions

Based on the comprehensive analysis of different mechanical properties for various types of fiber-reinforced self-compacting concrete, several key conclusions can be drawn:

**1. Compressive Strength:** SFSCC consistently exhibits the highest compressive strength improvements compared to plain SCC and other fiber-reinforced variants. SFSCC achieves a peak strength of 40.41 MPa at 0.5% fiber dosage, indicating its effectiveness in enhancing structural load-bearing capacity.

**2. Split Tensile Strength:** While SFSCC generally shows slightly lower split tensile strength values compared to plain SCC, both glass fiber reinforced SCC and polypropylene fiber reinforced SCC demonstrate increasing tensile strength with higher fiber dosages. This suggests that while there may be marginal trade-offs in tensile properties with steel fibers, overall tensile strength is significantly enhanced with fiber reinforcement.

**3. Flexural Strength:** All types of fiber-reinforced SCC exhibit notable improvements in flexural strength as fiber dosage increases from 0% to 1%. SFSCC leads in flexural strength enhancement, followed closely by GFSCC and PFSCC. This indicates the capacity of fiber reinforcement to improve the bending resistance and ductility of SCC, crucial for structural applications requiring enhanced flexural performance.

**4. Shear Strength:** SFSCC consistently demonstrates superior shear strength across different conditions and shear span to depth ratios compared to plain SCC, GFSCC, and PFSCC. The addition of steel fibers significantly enhances the shear resistance of SCC, making it particularly suitable for applications where shear loading is a critical design consideration.

Overall, the results underscore the effectiveness of fiber reinforcement—especially steel fibers—in enhancing the mechanical properties of self-compacting concrete. These findings have significant implications for structural engineers and designers, offering tailored solutions to optimize concrete performance under various loading conditions, thereby improving durability and structural integrity in construction applications. Further research could explore optimizing fiber dosages and combinations to achieve specific performance criteria tailored to diverse engineering needs.

# Author Contributions

H.D. has contributed to this study under the guidance of B.H.S. All authors reviewed and approved the final version of the manuscript.

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Data available on reasonable request.

# Conflicts of Interest

The authors declare no conflict of interest.

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