

A
Project Report On
**Experimental Study on Self-Compacting Concrete
with Steel Fibre for M30 Grade**

In partial fulfilment of the requirements for the degree of
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ABSTRACT

Self-Compacting Concrete (SCC) is an advanced construction material that can flow, spread, and consolidate under its own weight without the need for mechanical vibration. It offers superior workability, faster construction, reduced labour requirements, and improved performance in heavily reinforced structural elements. However, similar to conventional concrete, SCC exhibits relatively low tensile strength and is prone to cracking under tensile and flexural stresses. The incorporation of discrete steel fibres offers a proven route to overcome these limitations by enhancing tensile behaviour, ductility, toughness, and crack resistance.

The present investigation examines the fresh and hardened properties of M30 grade Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) containing hooked-end steel fibres at four dosages, namely 0.0%, 0.5%, 1.0%, and 1.5% by volume of concrete. The control SCC mix was designed in accordance with IS 10262:2019 and EFNARC (2005) guidelines using Portland Slag Cement, natural river sand of Zone II, 20 mm crushed granite coarse aggregate, and a polycarboxylate ether based superplasticizer at a water-to-cement ratio of 0.40.

Fresh concrete performance was evaluated through slump flow, T_{500} flow time, V-funnel, and L-Box tests as per EFNARC (2005). Hardened concrete properties were characterised through compressive strength (cube 150 mm), split tensile strength (cylinder 150 × 300 mm), and flexural strength (beam 100 × 100 × 500 mm) tests at 7 and 28 days of standard water curing. Surface hardness of the 28-day laboratory-cured cubes was additionally assessed non-destructively through rebound hammer measurements.

The results indicate that fibre incorporation reduces workability progressively while enhancing all mechanical properties. At 1.0% fibre dosage, the 28-day compressive, split tensile, and flexural strengths improved by 11.3%, 42.6%, and 41.4%, respectively, relative to the control mix. This dosage satisfied the EFNARC slump flow (SF2) and L-Box passing-ratio requirements but marginally exceeded the recommended T_{500} (5.1 s vs. 5 s) and V-funnel (11.2 s vs. 11 s) limits, and is therefore classified as partially self-compacting rather than fully compliant. The 1.5% mix produced small additional gains in tensile-mode strength (split tensile +5.0%, flexural +5.4% relative to 1.0%) at the cost of failing all four EFNARC criteria. On the combined evidence, 1.0% is selected as the optimum dosage — defined here as the highest fibre content that preserves acceptable placeability while delivering peak compressive strength — for the specific M30 SCC composition investigated (Portland Slag Cement, w/c = 0.40, hooked-end fibres of aspect ratio 60).

Keywords: Self-Compacting Concrete (SCC); Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC); M30 grade; EFNARC; slump flow; compressive strength; split tensile strength; flexural strength; hooked-end steel fibre; optimum fibre content.

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is the most widely used construction material in the world, valued for its compressive strength, mouldability, durability, and economic viability. It is deployed in nearly every category of infrastructure — buildings, bridges, dams, pavements, tunnels, and marine structures. Conventional vibrated concrete, however, relies on mechanical compaction for the removal of entrapped air and the achievement of a dense, homogeneous matrix. Where vibration is inadequate — as is often the case in heavily reinforced sections, complex formwork, or restricted-access placements — the finished concrete suffers from honeycombing, segregation, bleeding, and reduced long-term durability.

Self-Compacting Concrete (SCC), developed in Japan by Okamura and co-workers in the late 1980s, was conceived specifically to eliminate this dependence on external vibration. SCC is a highly flowable, non-segregating concrete that fills the formwork and encapsulates reinforcement solely under its own weight while remaining cohesive and stable. Adoption of SCC in production yields tangible benefits: improved construction quality, faster placement rates, reduced labour demand, elimination of vibration-induced noise, and enhanced structural durability.

1.2 Self-Compacting Concrete

Self-Compacting Concrete is characterised by three fresh-state properties defined in the EFNARC (2005) guidelines: filling ability — the capacity to flow into every corner of the formwork under gravity; passing ability — the capacity to pass through congested reinforcement without blockage; and segregation resistance — the capacity to retain a homogeneous distribution of the constituents during flow and after placement. These properties are conferred by a carefully balanced mix that combines a high powder content, a low coarse-aggregate volume, and a high-range water-reducing admixture (superplasticizer), and are quantified through workability tests such as the slump flow, T_{500} , V-funnel, and L-Box.

1.3 Steel Fibre Reinforced Concrete

Concrete performs excellently in compression but poorly in tension: its tensile strength is typically only 8–12% of its compressive strength, and the material fails in a brittle manner once micro-cracks coalesce. Traditional bar reinforcement effectively controls macro-cracks but is essentially passive at the micro-crack stage. Discrete fibres, distributed uniformly through the concrete volume, bridge cracks the instant they form and continue to transfer stress across them as they propagate.

Of the various fibre types available, steel fibres — particularly those with hooked ends — have proven the most effective for structural applications. The mechanical anchorage of the hook provides

substantially greater pull-out resistance than a straight fibre of the same aspect ratio, and the combination of high tensile strength (≥ 1000 MPa) and elastic modulus (≈ 200 GPa) of the fibre matches well with the surrounding cementitious matrix. Addition of steel fibres to concrete improves tensile and flexural strength, impact resistance, energy absorption, fatigue endurance, and post-cracking ductility, and dramatically reduces both the number and width of surface cracks.

1.4 Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC)

Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) unites the benefits of both technologies in a single material: the fresh-state performance of SCC and the mechanical enhancement of SFRC. It is well suited to precast elements, industrial floors, tunnel linings, bridge decks, and seismic-resistant structures where both ease of placement and enhanced structural performance are essential. Fibre addition, however, increases internal friction and reduces flowability; the fibre dosage must therefore be optimised to preserve self-compacting characteristics while realising the mechanical benefits.

1.5 Need for the Study

Although SCC and SFRC have each been the subject of extensive research, comparatively less experimental data are available on M30 grade SFRSCC prepared using Portland Slag Cement and locally sourced aggregates typical of Indian conditions. The optimum steel-fibre dosage — one that maximises mechanical performance without compromising the self-compacting character of the mix — remains poorly quantified for this specific class of concrete. A systematic laboratory investigation is therefore required to generate the data needed to guide practical use of SFRSCC in structural applications.

1.6 Objectives of the Study

The specific objectives of this investigation are as follows:

- To design an M30 grade Self-Compacting Concrete mix conforming to IS 10262:2019 and EFNARC (2005) using Portland Slag Cement, natural sand, 20 mm crushed granite coarse aggregate, and a polycarboxylate ether based superplasticizer.
- To evaluate the influence of hooked-end steel fibre addition at 0.0%, 0.5%, 1.0%, and 1.5% by volume of concrete on the fresh-state properties of SCC, quantified through slump flow, T_{500} flow time, V-funnel, and L-Box tests.
- To determine the hardened-state mechanical properties — compressive, split tensile, and flexural strength — at 7 and 28 days of standard water curing for each fibre dosage.
- To characterise the in-situ quality of the hardened concrete through non-destructive rebound hammer testing and to correlate the results with the 28-day compressive strength.
- To identify the optimum steel-fibre dosage that provides the best balance between fresh-state performance and mechanical enhancement for practical structural applications.

1.7 Scope of the Study

The scope of the present study is bounded as follows: the investigation is confined to M30 grade SCC produced with Portland Slag Cement at a fixed water-to-cement ratio of 0.40; only hooked-end steel fibres of length 30 mm and aspect ratio 60 are considered; the fibre dosage is varied over four levels (0.0%, 0.5%, 1.0%, 1.5% by volume); fresh-state assessment is limited to the four EFNARC tests listed above; hardened-state characterisation is limited to compressive, split tensile, and flexural strength at 7 and 28 days; and non-destructive testing is limited to the rebound hammer. Long-term durability and creep-shrinkage behaviour are outside the scope of the present work and are recommended for future investigation.

1.8 Organisation of the Report

The remainder of this dissertation is organised into six chapters. Chapter 2 presents a critical review of the published literature on SCC, SFRC, and SFRSCC and identifies the research gap that the present study addresses. Chapter 3 describes the constituent materials, mix design procedure, experimental matrix, specimen preparation, and testing methodology. Chapter 4 reports and discusses the fresh-state test results. Chapter 5 presents the hardened-state test results, including both destructive strength tests and the non-destructive rebound hammer test. Chapter 6 consolidates and interprets the experimental findings and identifies the optimum steel-fibre dosage. Chapter 7 draws the principal conclusions of the study and outlines the scope for future work. A comprehensive list of references consulted during the investigation is provided at the end of the report.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter presents a critical review of the published literature that forms the technical foundation of the present investigation. The review is organised in four parts: the origin and technological development of Self-Compacting Concrete; the mechanical role of steel fibres in cementitious matrices; a chronological summary of previous experimental studies on SFRSCC; and, finally, the identification of the research gap that the present investigation seeks to address.

2.2 Development of Self-Compacting Concrete

The concept of Self-Compacting Concrete was first advanced by Okamura and Ozawa at the University of Tokyo in 1986 as a response to the declining quality of concrete construction in Japan resulting from a shortage of skilled labour capable of performing correct vibration. The prototype mix, developed in 1988, achieved self-compacting behaviour by combining a low coarse-aggregate volume, a high powder content, and a high-range water-reducing admixture. Since then, extensive research has been conducted worldwide to refine mix-design methodologies, standardise fresh-state tests, and extend the material to structural applications. Formal design guidance is now available in EFNARC (2005), the European Guidelines for Self-Compacting Concrete, and in IS 15658:2006 and IS 10262:2019 at the national level.

2.3 Steel Fibre Reinforced Concrete

The addition of discrete steel fibres to concrete substantially improves its mechanical performance. The primary benefit is the enhancement of tensile and flexural strength: the fibres bridge cracks at the moment of initiation, transfer stress across the crack faces, and delay crack propagation. This crack-bridging mechanism produces the characteristic strain-hardening or strain-softening post-peak response of SFRC — in contrast to the brittle failure of plain concrete — and endows the material with substantially higher toughness, impact resistance, and energy-absorption capacity.

The pull-out behaviour of an individual fibre is governed by its geometry, aspect ratio, tensile strength, and the fibre-matrix bond. Hooked-end fibres, by virtue of their mechanical anchorage, develop pull-out loads several times greater than those of straight fibres of equal length and diameter. Consequently, hooked-end fibres have become the industry standard for structural applications. The reduced crack widths observed in SFRC also improve durability by limiting the ingress of moisture and aggressive chemicals; SFRC therefore performs well in industrial floors, airport pavements, tunnel linings, bridge decks, precast elements, and seismic-resistant structures.

2.4 Review of Previous Studies

Narayanan and Darwish (1987) studied the mechanical properties of Steel Fibre Reinforced Concrete and reported significant improvements in tensile strength, flexural strength, toughness, and crack resistance. Fibre bridging effectively delayed crack propagation, resulting in enhanced post-cracking behaviour and improved structural performance.

Khayat (1999) investigated the workability and rheological properties of SCC and identified the water-to-powder ratio and superplasticizer dosage as the two most influential mix parameters. The study reported that SCC delivers superior filling capacity and surface finish compared with conventional vibrated concrete, and highlighted segregation resistance as a critical performance criterion.

Nan Su et al. (2001) introduced a widely adapted mix design method centered on the packing factor of aggregates. This approach determines the minimum necessary binder paste to fill the voids between aggregates, making it highly effective for designing cost-efficient M30 mixes compared to traditional empirical methods.

Okamura and Ouchi (2003) formalised the theoretical basis of Self-Compacting Concrete and summarised the mix-design principles under which flowability and segregation resistance can be simultaneously achieved. They emphasised that the coarse-aggregate volume must be limited to about 50% of its dry-rodded value and that a high-range water-reducing admixture is essential for achieving high flow at low water content.

Grünewald (2004), in his doctoral work on performance-based design of SFRSCC, established the interdependence of fibre volume fraction, aspect ratio, and coarse-aggregate content in determining the fresh-state behaviour of the mix. Grünewald demonstrated that fibre addition beyond a critical volume fraction—typically 1.0–1.5% depending on the aggregate skeleton—causes a marked loss of flowability and passing ability.

EFNARC Guidelines (2005) provided the definitive standard criteria evaluating SCC fresh properties. Past studies confirm that for an M30 grade, a target slump flow range of 650–750 mm and an L-box blocking ratio above 0.8 are required to verify proper self-compacting behaviour before incorporating structural fibers.

Ferrara and Meda (2006) examined the flexural performance of SFRSCC and observed significant improvements in ductility and energy-absorption capacity, attributable to the crack-bridging action of the fibres. Their work highlighted the applicability of SFRSCC in precast structural elements requiring enhanced toughness.

Ferrara, Park, and Shah (2007) proposed a rational mix-design method for SFRSCC in which the aggregate skeleton is first optimised for the anticipated fibre content, and the paste volume is then adjusted to compensate for the fibre-induced flow resistance. Their approach yielded mixes with slump flow above 700 mm at fibre volume fractions of up to 1.0%.

Sahmaran, Yaman, and Tokyay (2009) reported that steel fibre addition to self-consolidating concrete containing high-volume fly ash improved compressive, tensile, and flexural strength and enhanced

resistance to cracking, while causing a moderate reduction in slump flow. They concluded that SFRSCC is particularly suitable for structures subjected to dynamic loading and harsh service environments.

Siddique et al. (2011) investigated the use of industrial by-products (like fly ash and silica fume) to enhance paste volume. Their findings indicated that filling the voids with mineral admixtures maintains the high flowability required for standard structural grades like M30 while reducing material costs.

Madandoust et al. (2012) analyzed the fresh and mechanical properties of self-compacting concrete containing various types of metallic and non-metallic fibers. Their research highlighted that the inclusion of hooked-end steel fibers markedly reduced the slump flow diameter and heightened the viscosity of the fresh mix. They concluded that to maintain compliance with standard self-compactability guidelines without causing segregation, an incremental increase in high-range water reducing admixtures (HRWRA) is essential as fiber content escalates.

Sujivitha and Maruthachalam (2012) performed an experimental evaluation on M30 grade self-compacting concrete blending mineral admixtures like fly ash. Their study focused on establishing an optimum base mix design prior to fiber addition, demonstrating that a replacement level of 25% fly ash yields ideal filling and passing abilities while satisfying the 28-day characteristic compressive strength targets of structural M30 grade concrete.

Aslani and Notoori (2012) investigated the mechanical properties of steel fiber-reinforced self-compacting concrete at elevated temperatures. Their experimental data mapped the degradation pathways of compressive strength, split tensile strength, and modulus of elasticity. They discovered that the interlocking network of steel fibers mitigates micro-fissure expansion, allowing the structural matrix to retain a higher percentage of its structural integrity compared to unreinforced plain SCC.

Khayat et al. (2014) observed that the aspect ratio (l/d) of steel fibers plays a critical role. Higher aspect ratios (>60) increase the inner network friction, requiring a higher dosage of Viscosity Modifying Agents (VMA) or Polycarboxylate Ether (PCE) superplasticizers to maintain EFNARC compliance.

Benaicha, Jalbaud, Burtschell, and Alaoui (2015) evaluated the fresh and hardened properties of steel-fibre reinforced SCC and reported that increasing fibre content improved compressive and tensile strengths but reduced workability, thereby emphasising the need to select fibre dosage carefully to preserve self-compacting characteristics.

Afroughsabet and Ozbakkaloglu (2015) studied the mechanical properties of high-performance concrete reinforced with steel and polypropylene fibres and reported improvements in compressive strength, tensile strength, toughness, and durability, with hooked-end steel fibres providing the greatest enhancement of tensile behaviour.

Yoo and Banthia (2016) presented a comprehensive review of fibre-reinforced concrete technologies and concluded that fibre geometry, aspect ratio, and dosage play decisive roles in determining the effectiveness of fibre reinforcement, with hooked-end steel fibres offering the best combination of pull-out capacity and workability.

Thomas and Ramaswamy (2017) evaluated the mechanical performance of structural beam elements cast with SFRSCC. Their findings showed that the integration of steel fibers significantly increased shear

capacity and reduced crack widths under service loads, suggesting that fiber reinforcement can partially substitute traditional stirrup reinforcement.

Chu and Kwan (2019) investigated hybrid and steel-fibre reinforced self-compacting concrete and demonstrated that steel fibres significantly improve crack resistance, tensile strength, and toughness, and contribute to a more uniform stress distribution within the matrix.

Mehdipour et al. (2020) concluded that hooked-end steel fibers cause greater resistance to fresh concrete flow than straight or crimped fibers, but they offer superior mechanical anchoring once the concrete hardens.

Ghorbani et al. (2020) examined the thresholds of structural steel fiber additions in self-compacting matrices, varying the volumetric content up to 1.65%. Their findings indicated that while workability steadily declines due to the surface area of the fibers, optimal structural performance is reached at higher fiber fractions, provided the water-to-binder ratio and high-range water reducers are precisely controlled to prevent the "balling effect".

Savaris and Laufer (2021) conducted a critical evaluation of the shear capacity and mechanical actions within steel fiber-reinforced self-compacting concrete structural elements. Their experimental testing validated that a uniform distribution of fibers substantially improves the post-peak behavior under shear stresses. The randomized micro-networks allow stress to redistribute evenly, minimizing catastrophic failures and confirming that fiber optimization can partially offset transverse reinforcement needs in moderate structural applications.

Mukilan (2024) focused on defining the exact ductile transition boundaries for fiber-reinforced SCC mixes. The researcher observed that a targeted addition of 1.25% hooked-end steel fibers yields a significant 14.4% increase in compressive strength alongside a dramatic increase in ductility. However, the study explicitly warned that pushing the fiber content past a 1.5% threshold degrades fresh EFNARC compliance due to a severe loss of internal matrix flowability.

Sathiparan and Subramaniam (2024) explored environmental and sustainability optimizations in advanced SCC systems by utilizing supplementary cementitious materials alongside fibers. They successfully mapped out how replacing portions of the binder matrix with mineral powders reduces the overall carbon footprint and heat of hydration without compromising the 28-day target characteristic strengths required for structural applications.

Recent Synthesis on Hybrid Frameworks (2024) focused on expanding the durability of fiber-reinforced SCC mixes. Investigations into transport properties showed that proper integration of hooked-end steel fibers reduces micro-crack connectivity, resulting in a marked reduction in saturated water absorption and chloride ion diffusion. This microstructural densification ensures that the steel fibers remain protected against early-stage corrosion while enhancing the service life of the structural element

2.5 Research Gap

The reviewed literature confirms that Self-Compacting Concrete and Steel Fibre Reinforced Concrete have each been extensively investigated, and that their combination in the form of SFRSCC has been shown to deliver both good workability and enhanced mechanical performance. However, most of the published work focuses on high-strength (M50–M80) or high-performance mixes designed with Ordinary Portland Cement. Comparatively fewer investigations have addressed the more common M30 grade prepared with Portland Slag Cement, which is widely used in India for reasons of durability, lower heat of hydration, and sustainability.

In addition, the reported optimum fibre content varies significantly across studies — typically in the range of 0.5% to 1.5% by volume — depending on fibre geometry, aggregate skeleton, and the specific performance criterion chosen. There is a need for systematic experimental data that jointly assess the fresh-state and hardened-state performance of M30 SFRSCC produced with locally available materials over a range of fibre dosages, so that a defensible optimum content can be recommended for this class of concrete.

2.6 Summary of Literature Review

The literature reviewed in this chapter establishes that Self-Compacting Concrete represents a significant advance in concrete technology by virtue of its ability to flow, fill, and consolidate under its own weight, and that discrete steel fibres are effective in enhancing the tensile, flexural, and post-cracking behaviour of cementitious matrices. The two technologies combine synergistically in Steel Fibre Reinforced Self-Compacting Concrete, provided that the fibre dosage is optimised to preserve fresh-state workability. The present study builds on this foundation by systematically characterising M30 grade SFRSCC prepared with Portland Slag Cement over four fibre dosages (0.0%, 0.5%, 1.0%, 1.5% by volume) and identifying the optimum content for practical structural applications.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter describes the constituent materials, mix-design procedure, experimental matrix, specimen preparation, curing regime, and testing methodology adopted in the present investigation. All materials were evaluated for conformance with the relevant Indian Standards prior to use, and all tests were carried out under controlled laboratory conditions at the Concrete Laboratory, Department of Civil Engineering, Cambridge Institute of Technology, Ranchi.

3.2 Materials Used

The concrete mixes were produced using Portland Slag Cement, natural river sand as fine aggregate, crushed granite as coarse aggregate, potable water, a polycarboxylate ether based high-range water-reducing admixture, and hooked-end steel fibres as discrete reinforcement. The properties of each constituent are described in the following subsections.

3.2.1 Cement

Portland Slag Cement (PSC) conforming to IS 455:2015 was used throughout the investigation. PSC was selected in preference to Ordinary Portland Cement because of its lower heat of hydration, improved resistance to chemical attack, better long-term durability, and reduced clinker content. The physical properties of the cement, determined through standard laboratory tests, are presented in Table 3.1.

Table 3.1 Physical properties of Portland Slag Cement

Property	Test result	IS 455:2015 requirement
Specific gravity	2.92	—
Standard consistency (%)	33	26 – 33
Initial setting time (min)	45	> 30
Final setting time (min)	495	< 600
Soundness (mm)	3	≤ 10
3-day compressive strength (MPa)	16.05	≥ 16
7-day compressive strength (MPa)	22.03	≥ 22
28-day compressive strength (MPa)	36.85	≥ 33

As shown in Table 3.1, all measured properties satisfy the requirements of IS 455:2015. The cement was therefore considered suitable for use in the present investigation.

3.2.2 Fine Aggregate

Natural river sand conforming to Zone II of IS 383:2016 was used as fine aggregate. Fine aggregate plays a critical role in Self-Compacting Concrete: it must be sufficiently well graded to fill the voids between the coarse aggregate particles, provide the cohesiveness needed for segregation resistance, and yet not consume excessive water. The physical properties of the fine aggregate are presented in Table 3.2.

Table 3.2 Physical properties of fine aggregate

Property	Test result
Grading zone (IS 383:2016)	Zone II
Specific gravity	2.65
Fineness modulus	2.68
Water absorption (%)	1.05
Bulk density (kg/m ³)	1580
Free moisture content (%)	1.20

The measured properties confirm that the fine aggregate is well graded, of low porosity, and of a specific gravity consistent with natural siliceous sand, and is therefore suitable for producing SCC with adequate flowability and stability.

3.2.3 Coarse Aggregate

Crushed granite aggregate of 20 mm nominal maximum size, conforming to IS 383:2016, was used as coarse aggregate. Coarse aggregate constitutes the largest volume fraction of concrete and exerts a significant influence on its strength, stiffness, and durability. The volume of coarse aggregate in SCC is deliberately kept lower than in conventional concrete in order to reduce inter-particle collisions and enable free flow through congested reinforcement. The physical properties of the coarse aggregate are presented in Table 3.3.

Table 3.3 Physical properties of coarse aggregate

Property	Test result
Type	Crushed granite
Nominal maximum size (mm)	20
Specific gravity	2.80
Water absorption (%)	1.02
Aggregate impact value (%)	9.67
Aggregate crushing value (%)	16.67
Bulk density (kg/m ³)	1620
Free moisture content (%)	0.50

The low impact and crushing values indicate that the coarse aggregate possesses adequate strength for structural concrete, and the specific gravity and water absorption are within the ranges recommended by IS 383:2016. The aggregate was therefore considered suitable for use in the present investigation.

3.2.4 Water

Clean potable water conforming to IS 456:2000 was used both for mixing and for curing of all concrete specimens. The water was free from harmful impurities such as chlorides, sulphates, and organic matter that could adversely affect the hydration of cement or the durability of the hardened concrete.

3.2.5 Superplasticizer

A polycarboxylate ether (PCE) based high-range water-reducing admixture conforming to IS 9103:1999 was used to achieve the target flowability of the SCC mixes at a low water-to-cement ratio. PCE-based admixtures act by both electrostatic and steric dispersion of cement particles and are the admixture of choice for modern SCC production. The properties of the superplasticizer are presented in Table 3.5, and the material is shown in Figure 3.4.

Table 3.5 Properties of superplasticizer

Property	Value
Type	Polycarboxylate ether based
Physical appearance	Brown liquid
Specific gravity	1.08
pH	≥ 6.0
Chloride content	Nil
Recommended dosage (% by weight of cement)	0.5 – 2.0
Adopted dosage in this study (%)	1.5

The chloride-free composition and the low recommended dosage make the admixture suitable for use in reinforced concrete under severe exposure conditions. The dosage of 1.5% by weight of cement was arrived at through trial mixes to achieve the target slump flow of the control SCC.

3.2.6 Steel Fibres

Hooked-end steel fibres were used as discrete reinforcement. The hooked geometry provides mechanical anchorage that develops full pull-out capacity before the fibre yields, and thereby maximises the crack-bridging contribution of the fibre. The properties of the fibres are presented in Table 3.4.

Table 3.4 Properties of hooked-end steel fibres

Property	Value
Type	Cold-drawn hooked-end steel fibre
Length, ℓ (mm)	30
Equivalent diameter, d (mm)	0.50
Aspect ratio (ℓ/d)	60
Tensile strength (MPa)	1100
Elastic modulus (GPa)	200
Density (kg/m^3)	7850

The aspect ratio of 60 was selected as a balance between crack-bridging efficiency (which improves with higher aspect ratio) and workability (which deteriorates with higher aspect ratio due to increased fibre-to-fibre interlock). Similar values have been reported as optimum for SFRSCC by Grünwald (2004) and Ferrara et al. (2007).

3.3 Mix Design

The concrete mix was designed as M30 grade Self-Compacting Concrete in accordance with IS 10262:2019 and the EFNARC (2005) guidelines. The mix-design procedure is summarised in the following sub-sections.

3.3.1 Target Mean Strength

The target mean compressive strength at 28 days was calculated using Equation 3.1:

$$f'_{ck} = f_{ck} + 1.65 S \quad (3.1)$$

where f'_{ck} is the target mean compressive strength at 28 days, f_{ck} is the characteristic compressive strength (30 MPa for M30 grade), and S is the standard deviation (5 N/mm² for M30 grade as per Table 2 of IS 10262:2019). Substituting these values gives:

$$f'_{ck} = 30 + 1.65 \times 5 = 38.25 \text{ N/mm}^2 \quad (3.2)$$

3.3.2 Selection of Water-to-Cement Ratio

From Figure 1 of IS 10262:2019, the free water-to-cement ratio required for a target strength of 38.25 N/mm² with Portland Slag Cement is approximately 0.43. However, in order to enhance durability and to accommodate the target slump flow requirement of Self-Compacting Concrete, a lower water-to-cement ratio of 0.40 was adopted for the present investigation. This value is well below the maximum of 0.45 permitted by IS 456:2000 for reinforced concrete under severe exposure.

3.3.3 Selection of Water Content and Cement Content

With a target free water content of 180 kg/m³ (arrived at through trial mixes with superplasticizer dosage of 1.5% by weight of cement) and a water-to-cement ratio of 0.40, the cement content was calculated as:

$$\text{Cement content} = \text{Water content} / (w/c) = 180 / 0.40 = 450 \text{ kg/m}^3 \quad (3.3)$$

The calculated cement content of 450 kg/m³ satisfies the minimum requirement of 320 kg/m³ specified in Table 5 of IS 456:2000 for severe exposure conditions.

3.3.4 Proportioning of Aggregates

For SCC, the coarse aggregate content was restricted to approximately 50% of its dry-rodded volume in order to promote free flow through reinforcement, in accordance with the recommendations of Okamura and Ouchi (2003). The corresponding volume of fine aggregate was calculated by mass

balance after accounting for the absolute volumes of cement, water, superplasticizer, and entrapped air (1.0% for 20 mm nominal aggregate). The final mix proportions are presented in Table 3.6.

Table 3.6 Mix proportions for M30 SCC (per m³)

Ingredient	Quantity (kg/m ³)	Specific gravity	Absolute volume (m ³)
Cement (PSC)	450	2.92	0.154
Fine aggregate	985	2.65	0.372
Coarse aggregate (20 mm)	780	2.80	0.279
Water	180	1.00	0.180
Superplasticizer (PCE, 1.5% of cement)	6.75	1.08	0.006
Entrapped air (1.0%)	—	—	0.010
Total (control SCC)	2401.75	—	1.001
Water-to-cement ratio	0.40	—	—
Mix ratio (cement : FA : CA, by mass)	1 : 2.19 : 1.73	—	—

The absolute-volume calculation shown in the last column of Table 3.6 confirms that the constituent volumes sum to 1.001 m³, i.e. essentially unity within rounding, as required by the mix-design procedure of IS 10262:2019. The fine-aggregate content of 985 kg/m³ is deliberately higher than that of conventional M30 vibrated concrete; this reflects the SCC requirement of a larger paste-and-fines volume to promote self-compacting behaviour, and is consistent with the approach recommended by Okamura and Ouchi (2003) and EFNARC (2005).

The mix proportions in Table 3.6 apply to the control SCC (0.0% fibre). For the SFRSCC mixes, hooked-end steel fibres were added at the target volume fractions (0.5%, 1.0%, and 1.5% by volume), corresponding to fibre masses of 39.25, 78.50, and 117.75 kg/m³ respectively. The added fibre volume (0.005, 0.010, and 0.015 m³ per m³ of concrete) was compensated by a proportional reduction in coarse aggregate volume so that the total volume of each mix remains at 1.000 m³ and the paste-content-controlled workability of the SCC matrix is preserved.

3.4 Experimental Matrix

The experimental programme consisted of one control SCC mix and three Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) mixes containing different dosages of hooked-end steel fibres. The four mixes and their designations are presented in Table 3.7.

Table 3.7 Experimental matrix

Mix ID	Steel fibre content (% by volume)	Fibre content (kg/m ³)	Description
SCC	0.0	0.0	Control Self-Compacting Concrete
SFRSCC-0.5	0.5	39.25	SCC with 0.5% steel fibres
SFRSCC-1.0	1.0	78.50	SCC with 1.0% steel fibres

Mix ID	Steel fibre content (% by volume)	Fibre content (kg/m ³)	Description
SFRSCC-1.5	1.5	117.75	SCC with 1.5% steel fibres

The selected dosages span the range 0.0% – 1.5% by volume, which brackets the optimum values reported in the literature (Grünwald 2004; Ferrara et al. 2007; Yoo and Banthia 2016) and permits identification of the dosage at which further additions cease to yield proportional mechanical benefits.

3.5 Specimen Preparation

Specimens were prepared under controlled laboratory conditions using a pan-type concrete mixer. All ingredient masses were weighed accurately to $\pm 0.5\%$ of the target value. The mixing sequence adopted was as follows: (i) fine and coarse aggregates were dry-mixed for 30 seconds; (ii) cement was added and dry-mixing was continued for a further 30 seconds; (iii) approximately 80% of the mixing water was introduced and mixing was continued for one minute; (iv) the superplasticizer, dissolved in the remaining water, was added and mixing was continued for two minutes; and (v) steel fibres, where applicable, were sprinkled in gradually over one minute to prevent fibre balling, followed by a final mixing of two minutes to achieve uniform fibre distribution.

Immediately after mixing, the fresh concrete was subjected to the EFNARC workability tests described in Chapter 4. The concrete was then poured into pre-oiled steel moulds without external vibration. For each mix, the specimens prepared are summarised in Table 3.8.

Table 3.8 Details of test specimens

Specimen type	Dimensions	Purpose	No. per mix
Cube	150 × 150 × 150 mm	Compressive strength (7 and 28 d)	6 (3 + 3)
Cylinder	150 mm × 300 mm	Split tensile strength (28 d)	3
Beam	100 × 100 × 500 mm	Flexural strength (28 d)	3
Cube	150 × 150 × 150 mm	Rebound hammer test (28 d)	3 (shared with compressive)

A total of twelve specimens per mix and forty-eight specimens across the four mixes were cast. All specimens were finished with a steel trowel and covered with damp hessian for the first 24 hours before demoulding.

3.6 Curing Procedure

After demoulding at an age of 24 ± 2 hours, all specimens were transferred to a curing tank containing clean potable water maintained at a temperature of 27 ± 2 °C, in accordance with IS 516:1959. The specimens were cured for a period of 7 or 28 days, depending on the intended testing age, and were removed from the tank not more than one hour before testing. The specimens were then wiped surface-dry, dimensioned, and weighed prior to being placed in the testing machine.

3.7 Testing Methodology

The performance of the SCC and SFRSCC mixes was evaluated through a two-part testing programme: fresh-state tests conducted immediately after mixing, and hardened-state tests conducted at specified ages after curing. The fresh-state tests followed the EFNARC (2005) guidelines and comprised the slump flow test, T_{500} flow time, V-funnel test, and L-Box test. The hardened-state destructive tests were conducted in accordance with IS 516:1959 and IS 5816:1999, and comprised the compressive strength test on cubes, the split tensile strength test on cylinders, and the flexural strength test on beams. Finally, the in-situ quality of the hardened concrete was assessed non-destructively using the rebound hammer in accordance with IS 13311 (Part 2):1992. Detailed procedures for each test are presented in Chapters 4 and 5 alongside the respective results.

CHAPTER 4

TESTS ON FRESH CONCRETE

4.1 Introduction

The fresh-state properties of Self-Compacting Concrete determine its ability to be placed and consolidated without segregation and without external vibration. This chapter describes the four EFNARC (2005) tests employed in the present investigation — slump flow, T_{500} flow time, V-funnel, and L-Box — and reports and discusses the results obtained for the four mixes listed in Table 3.7. All tests were conducted immediately after mixing, at a fresh-concrete temperature of 27 ± 2 °C.

4.2 Slump Flow Test

The slump flow test provides a direct measure of the filling ability of SCC. An Abrams slump cone is filled with fresh concrete without any tamping or vibration, lifted vertically, and the mean diameter of the resulting concrete spread is measured in two perpendicular directions. The average diameter, calculated using Equation 4.1, is reported as the slump flow:

$$D_{avg} = (D_1 + D_2) / 2 \quad (4.1)$$

where D_1 and D_2 are the two perpendicular spread diameters in mm. According to EFNARC (2005), acceptable SCC lies in the range 550 – 850 mm, with the SF2 class (660 – 750 mm) recommended for normal structural applications. The measured slump flow values are presented in Table 4.1.

Table 4.1 Slump flow test results

Mix ID	D_1 (mm)	D_2 (mm)	Slump flow, D_{avg} (mm)	EFNARC class
SCC	695	705	700	SF2
SFRSCC-0.5	680	690	685	SF2
SFRSCC-1.0	655	665	660	SF2 (lower limit)
SFRSCC-1.5	615	625	620	SF1

The variation of slump flow with steel fibre content is shown graphically in Figure 4.1.

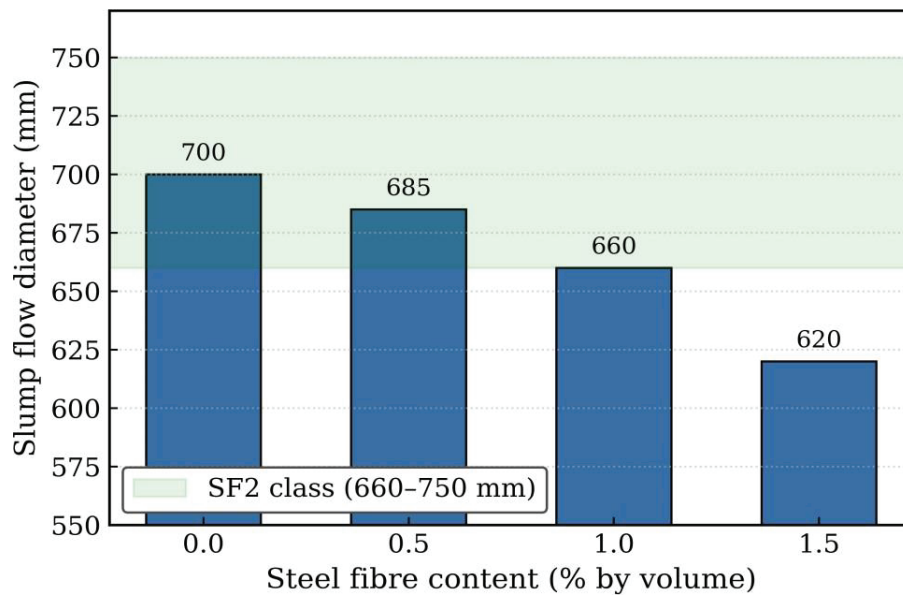


Figure 4.1 Variation of slump flow diameter with steel fibre content



Figure 4.1 shows a progressive decrease in slump flow with increasing fibre content: from 700 mm for the control SCC to 620 mm at 1.5% fibre — a reduction of 11.4%. The mixes at 0.0%, 0.5%, and 1.0% dosage all satisfy the SF2 class (660 – 750 mm), while the 1.5% mix drops into the SF1 class (550 – 650 mm). This behaviour is a direct consequence of the increased internal friction and reduced free paste content that accompany fibre addition: each fibre acts as an obstacle to flow, and the fibre network dissipates a portion of the gravitational driving stress. The trend and its magnitude are in close agreement with the observations of Grünwald (2004) and Ferrara et al. (2007) on hooked-end SFRSCC of similar aspect ratio.

4.3 T_{500} Flow Time

The T_{500} time is a measure of the plastic viscosity of SCC. It is recorded as the time (in seconds) taken by the leading edge of the concrete to reach a spread diameter of 500 mm during the slump flow test. According to EFNARC (2005), acceptable SCC lies in the range $T_{500} = 2 - 5$ s, with class VS1 (< 2 s)

indicating low viscosity and class VS2 (≥ 2 s) indicating moderate viscosity suitable for controlling segregation. The measured T_{500} values are presented in Table 4.2.

Table 4.2 T_{500} flow time results

Mix ID	T_{500} (s)	EFNARC class
SCC	3.2	VS2
SFRSCC-0.5	4.0	VS2
SFRSCC-1.0	5.1	Above VS2 limit
SFRSCC-1.5	6.5	Above VS2 limit

The variation of T_{500} time with fibre content is shown in Figure 4.2.

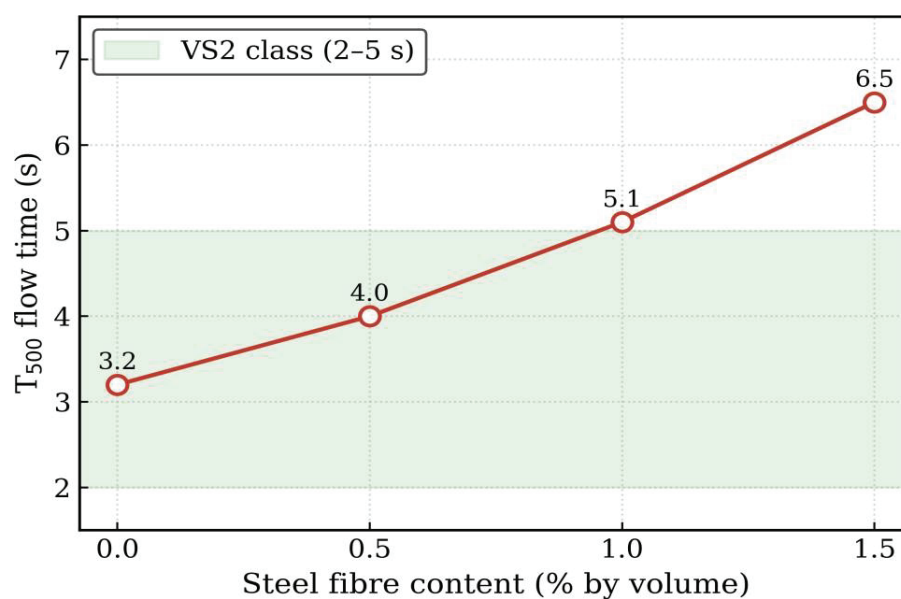


Figure 4.2 Variation of T_{500} flow time with steel fibre content

Figure 4.2 shows that T_{500} increases from 3.2 s for the control SCC to 6.5 s for SFRSCC-1.5%. The control and 0.5% mixes lie comfortably within the VS2 class (2 – 5 s), the 1.0% mix marginally exceeds the upper limit, and the 1.5% mix departs significantly from the recommended range. The trend reflects the increase in plastic viscosity caused by the fibre network: the leading edge of the flowing concrete must displace fibres in addition to the aggregate skeleton, and this additional resistance manifests as a longer time to reach 500 mm spread. Similar behaviour has been reported by Sahmaran et al. (2009) and Chu and Kwan (2019).

4.4 V-Funnel Test

The V-funnel test provides an alternative measure of the viscosity and filling ability of SCC. A V-shaped steel funnel of prescribed dimensions is filled to the brim with fresh concrete, and the time taken for the concrete to fully discharge after opening the bottom trap is recorded. According to EFNARC

(2005), acceptable SCC lies in the range 6 – 12 s, with class VF1 (7 – 11 s) recommended for structural applications. The measured V-funnel times are presented in Table 4.3.

Table 4.3 V-funnel flow time results

Mix ID	V-funnel flow time (s)	EFNARC class
SCC	8.5	VF1
SFRSCC-0.5	9.8	VF1
SFRSCC-1.0	11.2	VF2 (upper)
SFRSCC-1.5	13.5	Above VF2 limit

The variation of V-funnel time with fibre content is shown in Figure 4.3.

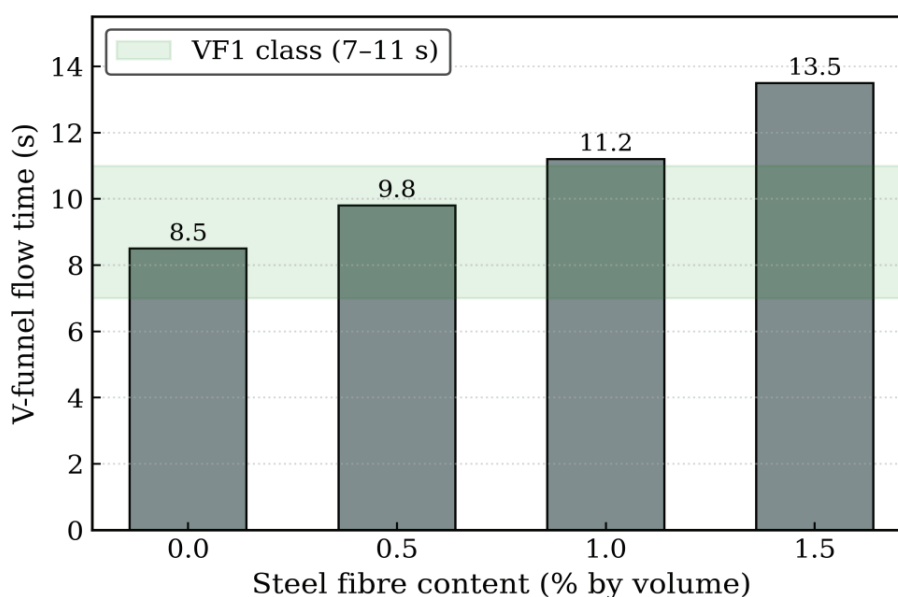


Figure 4.3 Variation of V-funnel flow time with steel fibre content

Figure 4.3 shows a monotonic increase in V-funnel time with fibre content, from 8.5 s for the control to 13.5 s at 1.5% fibre — an increase of 59%. The control and 0.5% mixes satisfy the VF1 class; the 1.0% mix lies at the upper boundary of the VF2 class (9 – 25 s in EFNARC 2005), while the 1.5% mix indicates a viscosity too high for reliable self-compacting behaviour under normal placement conditions. The V-funnel results are fully consistent with the T_{500} observations of the preceding section, in that both tests reflect the same underlying rheological property, the plastic viscosity.

4.5 L-Box Test

The L-Box test evaluates the passing ability of SCC through congested reinforcement. Fresh concrete is filled into the vertical arm of an L-shaped box, a gate is opened, and the concrete flows through three vertical reinforcement bars (spacing 41 mm clear) into the horizontal arm. The heights of concrete at

the far end of the horizontal arm (H_2) and at the base of the vertical arm (H_1) are measured, and the passing ratio is calculated using Equation 4.2:

$$\text{Passing ratio} = H_2 / H_1 \quad (4.2)$$

where H_1 and H_2 are the heights of concrete at the base of the vertical arm and at the far end of the horizontal arm respectively. According to EFNARC (2005), the passing ratio should not be less than 0.80 for concrete to be classified as self-compacting. The measured L-Box results are presented in Table 4.4.

Table 4.4 L-Box passing ratio results

Mix ID	H_1 (mm)	H_2 (mm)	Passing ratio (H_2/H_1)	EFNARC assessment
SCC	150	147	0.98	Acceptable
SFRSCC-0.5	150	138	0.92	Acceptable
SFRSCC-1.0	150	128	0.85	Acceptable
SFRSCC-1.5	150	114	0.76	Below EFNARC limit

The variation of the L-Box passing ratio with fibre content is shown in Figure 4.4.

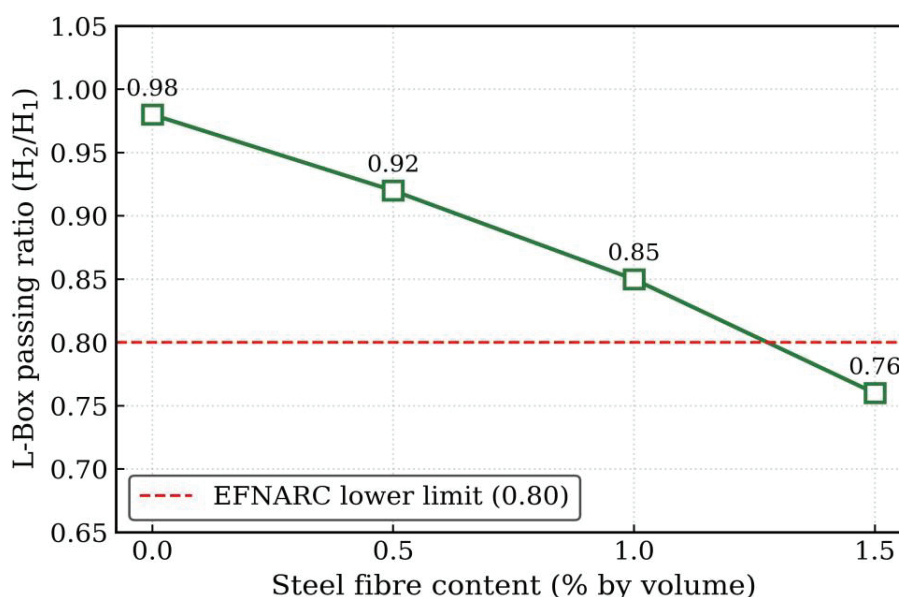


Figure 4.4 Variation of L-Box passing ratio with steel fibre content

Figure 4.4 shows a monotonic decrease in the passing ratio from 0.98 for the control SCC to 0.76 for SFRSCC-1.5%. The control, 0.5%, and 1.0% mixes all exceed the EFNARC lower limit of 0.80 and are therefore acceptable as passing SCC. The 1.5% mix, however, falls below this limit, indicating that the fibre network at that dosage is too dense to pass freely between the reinforcement bars. Visual observation of the L-Box test at 1.5% fibre confirmed local fibre accumulation just upstream of the reinforcement gate, which is the classic mechanism of fibre-induced blockage described by Grünewald

(2004). The L-Box therefore provides the clearest single-test indication that 1.0% by volume represents the practical upper limit of fibre dosage for the SCC matrix used in the present investigation.

4.6 Summary of Fresh Concrete Performance

The fresh-state results across all four tests are consolidated in Table 4.5 for direct comparison against the EFNARC (2005) limits.

Table 4.5 Summary of fresh concrete properties against EFNARC (2005) limits

Test	EFNARC limit	SCC	SFRSCC-0.5	SFRSCC-1.0	SFRSCC-1.5
Slump flow (mm)	660 – 750 (SF2)	700 ✓	685 ✓	660 ✓	620 ✗
T ₅₀₀ (s)	2 – 5 (VS2)	3.2 ✓	4.0 ✓	5.1 ✗	6.5 ✗
V-funnel (s)	7 – 11 (VF1)	8.5 ✓	9.8 ✓	11.2 ✗	13.5 ✗
L-Box ratio	≥ 0.80	0.98 ✓	0.92 ✓	0.85 ✓	0.76 ✗

Table 4.5 shows that only the control SCC and SFRSCC-0.5% satisfy all four EFNARC criteria simultaneously and are therefore fully compliant Self-Compacting Concrete. SFRSCC-1.0% satisfies the two filling- and passing-related criteria (slump flow and L-Box) but marginally exceeds the two viscosity-related criteria (T₅₀₀ by 0.1 s, and V-funnel by 0.2 s), indicating a plastic viscosity slightly above the recommended EFNARC range. This mix is therefore classified in the present study as partially self-compacting: it remained placeable in the laboratory without vibration, but it does not meet the full four-test EFNARC specification. It is retained in the analysis of hardened properties because it delivers the peak compressive strength (see Chapter 5) and is directly relevant to identifying the optimum fibre content. SFRSCC-1.5% fails all four EFNARC criteria and cannot be classified as Self-Compacting Concrete under EFNARC (2005); it is retained solely to establish the upper bound of the fibre-dosage window.

CHAPTER 5

TESTS ON HARDENED CONCRETE

5.1 Introduction

This chapter reports the hardened-state performance of the four mixes described in Table 3.7. Three destructive strength tests were carried out — compressive strength on cubes, split tensile strength on cylinders, and flexural strength on beams — supplemented by non-destructive rebound hammer measurements at 28 days. All destructive tests were carried out in a 2000 kN capacity servo-hydraulic testing machine at the Concrete Laboratory, Department of Civil Engineering, Cambridge Institute of Technology, Ranchi. For every strength value reported, three specimens were tested and the arithmetic mean is presented.

5.2 Compressive Strength Test

The compressive strength test was carried out on 150 mm cube specimens in accordance with IS 516:1959. After surface drying, each specimen was placed centrally between the platens of the testing machine and load was applied at a rate of 140 kg/cm²/min until failure. The compressive strength was calculated using Equation 5.1:

$$f_c = P / A \quad (5.1)$$

where f_c is the compressive strength in N/mm², P is the ultimate failure load in N, and A is the loaded cross-sectional area (22 500 mm² for a 150 mm cube). The compressive strength results obtained at 7 and 28 days are presented in Table 5.1.

Table 5.1 Compressive strength results at 7 and 28 days

Mix ID	Fibre content (%)	7-day strength (MPa)	28-day strength (MPa)	7-d / 28-d ratio
SCC	0.0	26.4	38.8	0.68
SFRSCC-0.5	0.5	28.5	41.6	0.69
SFRSCC-1.0	1.0	30.1	43.2	0.70
SFRSCC-1.5	1.5	29.4	42.4	0.69

The variation of compressive strength with steel fibre content at both ages is shown in Figure 5.1.

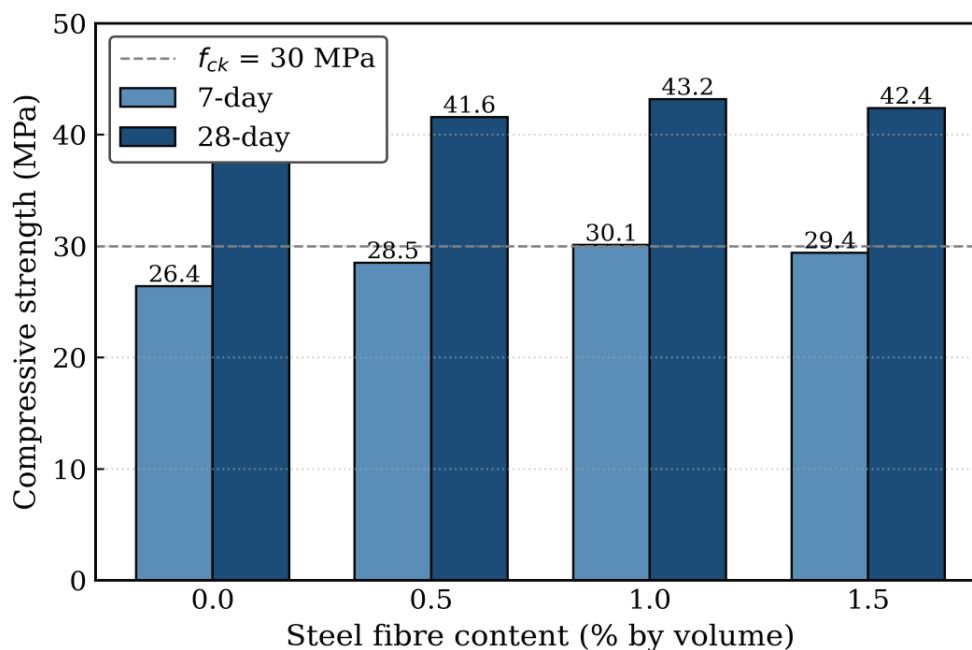


Figure 5.1 Compressive strength of SCC and SFRSCC mixes at 7 and 28 days

Figure 5.1 shows that the 28-day mean compressive strength increases from 38.8 MPa for the control SCC to a peak of 43.2 MPa at 1.0% fibre dosage — a gain of 11.3% — before falling marginally to 42.4 MPa at 1.5%. All four mean strengths exceed 30 MPa; the demonstration of characteristic strength in the statistical sense of IS 456:2000 would additionally require the standard-deviation-based acceptance calculation and is discussed in Section 6.6. The 7-day to 28-day strength ratio remains close to 0.69 across all mixes, showing that the strength-development curves are broadly parallel over the fibre-content range studied. This observation is consistent with fibre addition acting as passive, inclusion-type reinforcement rather than modifying the cement-hydration process itself; a direct verification would require isothermal calorimetry or non-evaporable-water measurements, which are outside the scope of the present investigation.

The strength gain observed up to 1.0% dosage is consistent with the crack-arresting action of fibres reported in the literature (Narayanan and Darwish 1987; Ferrara et al. 2007), in which the fibres delay the coalescence of micro-cracks into macro-cracks under compressive loading. The strength reduction observed at 1.5% coincides with the workability loss reported in Chapter 4 (slump flow drops into SF1 class, L-Box below the 0.80 EFNARC limit). Under these fresh-state conditions, fibre balling and locally incomplete compaction are plausible mechanisms responsible for the reversal of the trend and have been invoked by Grünwald (2004) and Sahmaran et al. (2009) to explain analogous observations; the present investigation, however, did not include the microstructural (e.g. micro-CT or optical porosity) measurements needed to confirm these mechanisms directly. Similar peak-then-decline compressive-strength behaviour has been reported by Sahmaran et al. (2009) and Afroughsabet and Ozbakkaloglu (2015) for hooked-end SFRSCC of comparable fibre geometry.

5.3 Split Tensile Strength Test

The split tensile strength was determined on 150 mm × 300 mm cylindrical specimens at 28 days in accordance with IS 5816:1999. Each specimen was placed horizontally between the platens with plywood strips at the loading contacts, and load was applied at a controlled rate until failure by vertical splitting. The split tensile strength was calculated using Equation 5.2:

$$f_{st} = 2P / (\pi D L) \quad (5.2)$$

where f_{st} is the split tensile strength in N/mm², P is the ultimate load in N, D is the cylinder diameter (150 mm), and L is the cylinder length (300 mm). The results are presented in Table 5.2.

Table 5.2 Split tensile strength results at 28 days

Mix ID	Fibre content (%)	Ultimate load (kN)	Split tensile strength (MPa)	Increase over control (%)
SCC	0.0	229	3.24	—
SFRSCC-0.5	0.5	279	3.95	+21.9
SFRSCC-1.0	1.0	327	4.62	+42.6
SFRSCC-1.5	1.5	343	4.85	+49.7

The variation of split tensile strength with fibre content is shown in Figure 5.2.

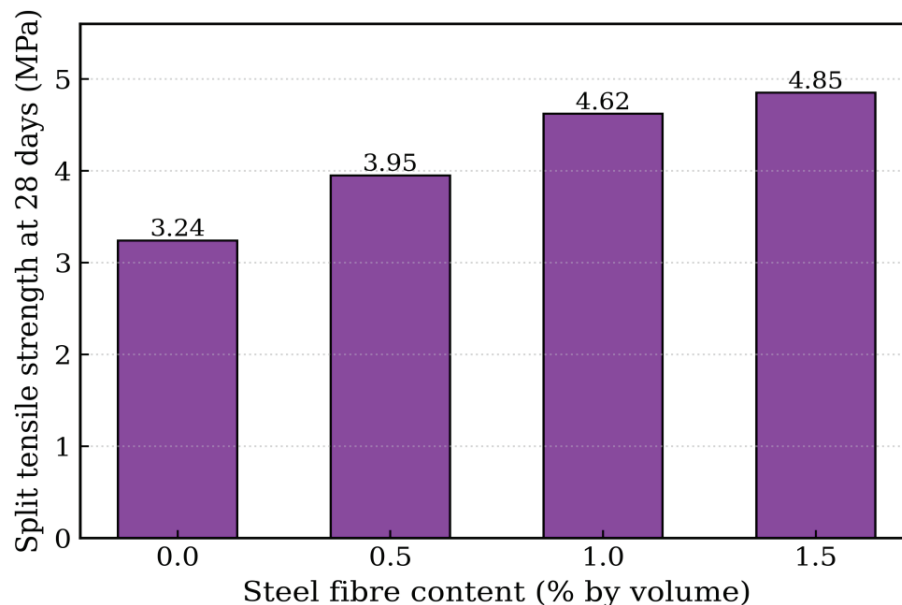


Figure 5.2 Split tensile strength of SCC and SFRSCC mixes at 28 days

Figure 5.2 shows that split tensile strength increases monotonically with fibre content, from 3.24 MPa for the control to 4.85 MPa at 1.5% fibre — an increase of 49.7%. The improvement is considerably greater than that observed for compressive strength because the failure mechanism in the split tensile test is dominated by crack propagation across the vertical diametral plane. In the control SCC, this failure is essentially brittle: once the tensile cracking stress is reached, the crack propagates almost

instantaneously through the specimen. In the SFRSCC mixes, the fibres crossing the incipient crack are activated as soon as the crack opens, and their pull-out resistance provides an additional load-carrying mechanism that continues to operate as the crack widens. The observed magnitude of improvement is consistent with the values reported by Narayanan and Darwish (1987) and Yoo and Banthia (2016) for hooked-end fibres of similar aspect ratio.

5.4 Flexural Strength Test

The flexural strength (modulus of rupture) was determined on $100 \times 100 \times 500$ mm beam specimens under two-point loading over a clear span of 400 mm in accordance with IS 516:1959. The flexural strength was calculated using Equation 5.3:

$$fb = PL / (bd^2) \quad (5.3)$$

where fb is the flexural strength in N/mm^2 , P is the ultimate load in N , L is the clear span (400 mm), and b and d are the width and depth of the beam (100 mm each). The results are presented in Table 5.3.

Table 5.3 Flexural strength results at 28 days

Mix ID	Fibre content (%)	Ultimate load (kN)	Flexural strength (MPa)	Increase over control (%)
SCC	0.0	10.9	4.35	—
SFRSCC-0.5	0.5	13.2	5.28	+21.4
SFRSCC-1.0	1.0	15.4	6.15	+41.4
SFRSCC-1.5	1.5	16.2	6.48	+49.0

The variation of flexural strength with fibre content is shown in Figure 5.3.

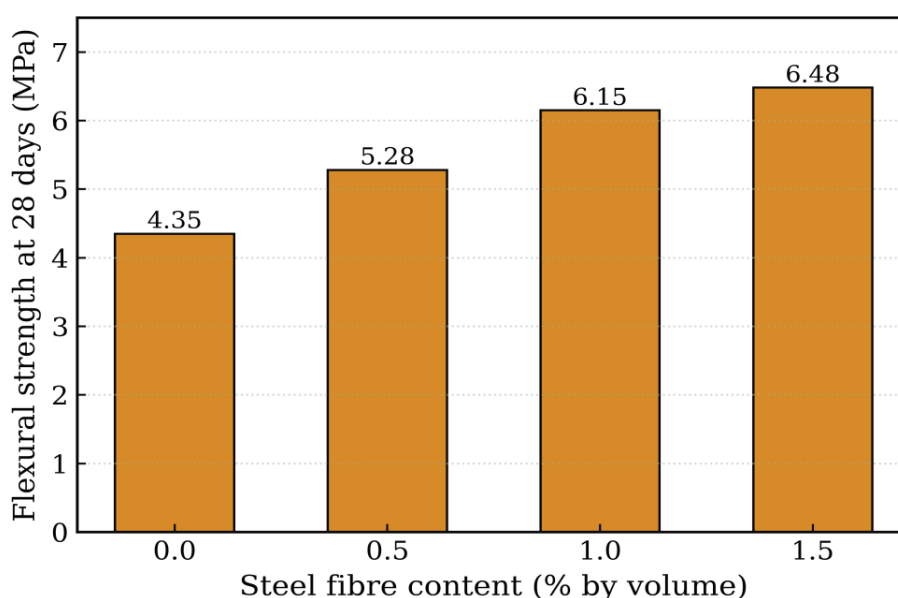


Figure 5.3 Flexural strength of SCC and SFRSCC mixes at 28 days

Figure 5.3 shows that flexural strength increases monotonically from 4.35 MPa for the control SCC to 6.48 MPa at 1.5% fibre — an increase of 49.0% that is essentially identical in magnitude to the improvement in split tensile strength. This is consistent with theoretical expectations: both tests probe the tensile behaviour of concrete and the same crack-bridging mechanism operates in each. The 28-day flexural-to-compressive strength ratio increases from 0.112 for the control SCC to 0.153 at 1.5% fibre, confirming that fibre addition disproportionately enhances tensile-mode performance. Beyond 1.0% dosage the marginal gain diminishes, mirroring the diminishing return observed in the compressive test and reflecting the practical upper bound on fibre content imposed by workability and fibre balling. Comparable observations have been reported by Ferrara and Meda (2006) and Chu and Kwan (2019).

5.5 Rebound Hammer Test (Non-Destructive Assessment of Surface Hardness)

The rebound hammer provides a non-destructive assessment of the surface hardness of hardened concrete, which is empirically correlated with compressive strength. In the present investigation, a Schmidt N-type rebound hammer was applied to the 28-day laboratory-cured cube specimens in accordance with IS 13311 (Part 2):1992. It should be noted that the measurements were carried out on standard laboratory-cured cubes and not on in-situ concrete elements; the terminology adopted throughout is therefore ‘surface-hardness assessment of hardened concrete’ rather than in-situ quality assessment. For each cube, ten readings were taken on the trowelled face at points not less than 25 mm from the edge and from one another, and the mean rebound number was recorded. The results are presented in Table 5.4.

Table 5.4 Rebound hammer test results at 28 days

Mix ID	Fibre content (%)	Mean rebound number (n=10)	Standard deviation	Estimated strength (MPa)*
SCC	0.0	32.0	1.4	37.5
SFRSCC-0.5	0.5	33.0	1.5	40.2
SFRSCC-1.0	1.0	34.0	1.6	42.9
SFRSCC-1.5	1.5	33.5	1.7	41.6

** Estimated from the manufacturer's default correlation curve for horizontal orientation, given here for reference only. The instrument-specific correlation for the mixes tested is developed in Section 6.5.*

The variation of rebound number with fibre content is shown in Figure 5.4.

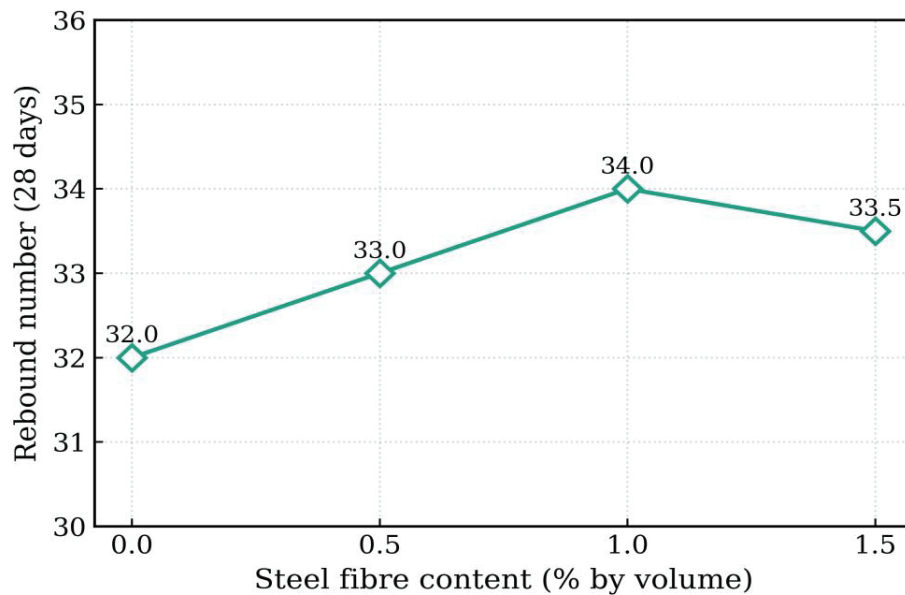


Figure 5.4 Variation of rebound number with steel fibre content

Figure 5.4 shows that the mean rebound number follows the same qualitative trend as the compressive strength — increasing up to 1.0% dosage and declining slightly at 1.5%. The absolute rebound values (32.0 – 34.0) place all mixes in the ‘good’ quality band per IS 13311 (Part 2):1992, and the low standard deviations (1.4 – 1.7) indicate homogeneous surface hardness within each cube. It should be emphasised that the rebound hammer characterises only the near-surface (typically 25 – 30 mm) hardness of the concrete and cannot substitute for the destructive cube test. Its role in the present study is therefore comparative — to verify that the trends observed in the destructive tests are also reflected in the near-surface response — rather than absolute strength prediction. A preliminary mix-specific calibration developed from the present dataset is presented in Section 6.5.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Overview

This chapter consolidates the fresh- and hardened-state results reported in Chapters 4 and 5, examines the underlying material mechanisms responsible for the observed trends, benchmarks the observations against the published literature, and identifies the optimum steel-fibre dosage for the M30 grade Self-Compacting Concrete considered in the present investigation.

6.2 Effect of Steel Fibres on Fresh Properties

The fresh-state results reported in Chapter 4 show a consistent, monotonic deterioration of workability with increasing fibre content. Slump flow decreased by 11.4%, T_{500} time increased by 103%, V-funnel time increased by 59%, and the L-Box passing ratio decreased by 22% as the fibre dosage was raised from 0.0% to 1.5%. This behaviour is explained by two mechanisms operating in combination. First, each fibre acts as a discrete obstacle to flow and, being effectively rigid at the scale of the concrete matrix, resists the shear deformation that flow requires. Second, at high dosages the fibres begin to entangle and interact with the coarse aggregate skeleton, forming a semi-continuous network that dramatically increases the yield stress and plastic viscosity of the mix. Grünwald (2004) formalised this as a critical-volume-fraction concept and reported that for hooked-end fibres of aspect ratio 60, the critical fraction lies close to 1.0% by volume for the type of coarse aggregate skeleton employed here. The present observations are in excellent agreement with this finding: the 1.0% mix marks the practical transition from fully self-compacting behaviour to fibre-limited flow.

6.3 Effect of Steel Fibres on Mechanical Properties

The mechanical results reported in Chapter 5 show that fibre addition enhances all three measured strengths, but to markedly different degrees. Compressive strength increases modestly (by 11.3% at the optimum 1.0% dosage), while split tensile and flexural strengths increase substantially (by 42.6% and 41.4% respectively at the same dosage, and by close to 50% at 1.5%). The percentage improvements are consolidated in Table 6.1 and displayed graphically in Figure 6.1.

Table 6.1 Percentage improvement in mechanical properties over control SCC

Fibre content (%)	Compressive (28 d)	Split tensile (28 d)	Flexural (28 d)
0.0	—	—	—
0.5	+7.2%	+21.9%	+21.4%
1.0	+11.3%	+42.6%	+41.4%
1.5	+9.3%	+49.7%	+49.0%

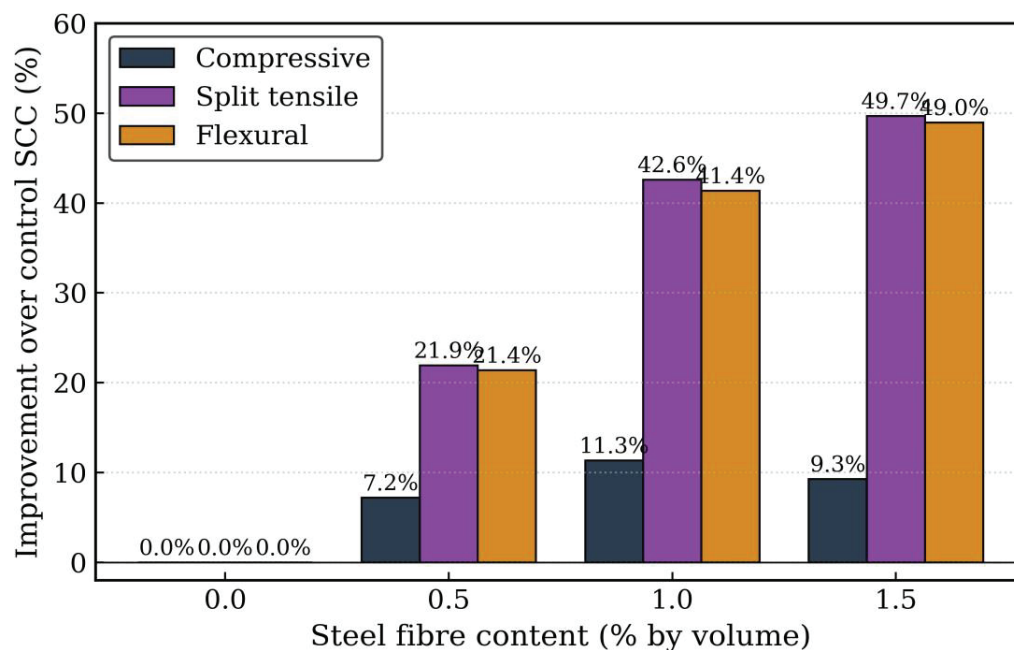


Figure 6.1 Percentage improvement in mechanical properties over control SCC

Figure 6.1 makes the differential effect immediately apparent: the compressive-strength curve peaks and declines, while the split tensile and flexural curves rise steeply up to 1.0% and continue to rise, though more slowly, up to 1.5%. This differential response is a direct consequence of the different failure mechanisms of the three tests. Compressive failure of concrete is initiated by the coalescence of vertical splitting cracks; the fibres delay this coalescence but cannot prevent it, and the modest strength gain is offset at high dosages by the compaction defects introduced by poor workability. Tensile-mode failure — as probed by the split tensile and flexural tests — is instead controlled directly by the crack-bridging capacity of the fibres crossing the fracture plane, and therefore responds strongly and roughly linearly to fibre dosage. The observed strength ratios (approximately +40% at 1.0% dosage) are in close agreement with those reported by Narayanan and Darwish (1987), Yoo and Banthia (2016), and Chu and Kwan (2019) for hooked-end fibres of aspect ratio 60.

6.4 Mechanism of Crack Bridging (Literature-Supported Interpretation)

The present programme measured strengths in the compressive, split tensile, and flexural modes; direct measurements of fracture energy, post-cracking response, or fibre-matrix bond were not carried out. The mechanistic interpretation offered here is therefore a hypothesis drawn from the published literature on hooked-end SFRSCC, presented to rationalise the observed strength trends rather than as a directly measured outcome of the present investigation.

According to this literature-supported interpretation, the enhanced tensile-mode behaviour of SFRSCC results from the sequential activation of fibres bridging an opening crack (Naaman 2003; Bentur and

Mindess 2007; Yoo and Banthia 2016). When a micro-crack forms in a fibre-reinforced matrix, the fibres crossing the crack plane resist the opening displacement through a combination of chemical bond, frictional slip along the fibre-matrix interface, and — in the case of hooked-end fibres — mechanical anchorage as the deformed end is progressively straightened during pull-out. Full straightening of a hooked end requires substantial energy dissipation, and this energy is subtracted from the elastic energy available to drive crack propagation. The crack-bridging efficiency is proportional to the number of fibres crossing the crack plane, which for randomly oriented fibres scales linearly with volume fraction. The observed near-linear increase of split tensile and flexural strengths with fibre content up to 1.0% (Table 6.1) is fully consistent with this scaling and is therefore consistent with the crack-bridging mechanism described in the literature.

The diminishing marginal benefit observed between 1.0% and 1.5% coincides with the loss of self-compacting behaviour reported in Chapter 4 (slump flow falls into SF1 class; L-Box drops below the 0.80 EFNARC limit). Under these fresh-state conditions, two mechanisms have been proposed in the literature to account for the reduced strength gain: (i) fibre balling, in which fibres agglomerate during mixing and introduce macroscopic voids that themselves act as crack initiators (Grünwald 2004); and (ii) reduced densification of the interfacial transition zone (ITZ) surrounding each fibre due to incomplete compaction, which is expected to weaken the fibre-matrix bond and reduce the pull-out capacity (Bentur and Mindess 2007). The present investigation did not include the micro-imaging (e.g. optical porosity or micro-CT) or the fibre pull-out tests required to confirm these mechanisms directly; they are offered here as plausible literature-supported explanations for the observed trend rather than as measured findings.

6.5 Correlation of Rebound Number with Compressive Strength

The rebound hammer results of Section 5.5 can be correlated with the 28-day cube compressive strengths to develop a mix-specific calibration curve. The correlation is presented in Figure 6.2.

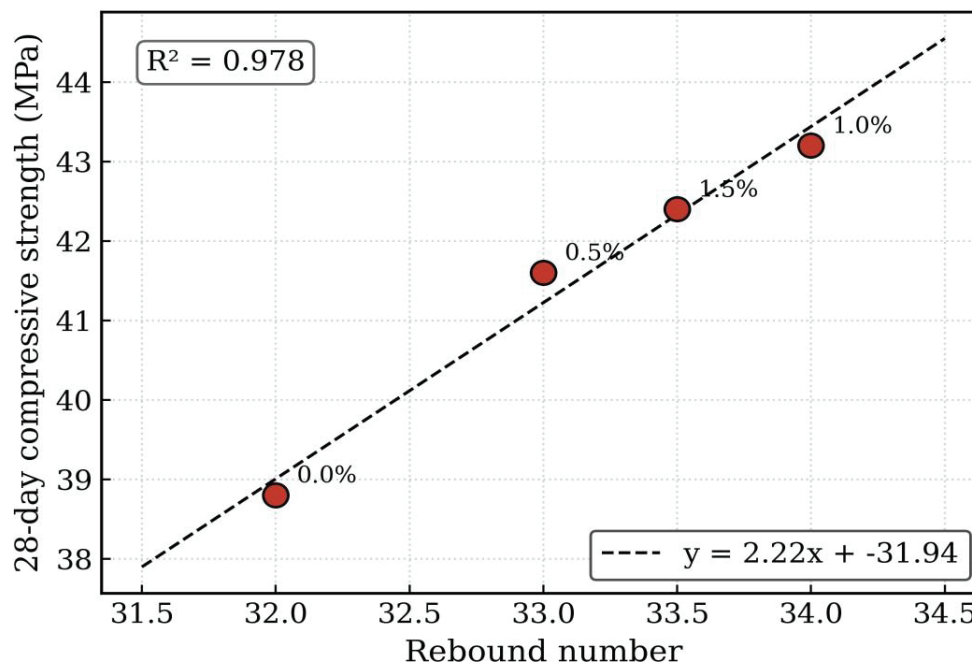


Figure 6.2 Correlation between rebound number and 28-day compressive strength

Figure 6.2 shows a strong linear correlation between rebound number and 28-day mean compressive strength for the four mixes, with a coefficient of determination $R^2 = 0.978$ and a best-fit relationship $f_c = 2.22 R - 31.94$, where R is the mean rebound number. This correlation is based on only four mix-level data points (one per fibre dosage) and must therefore be regarded as a preliminary mix-specific relationship valid only within the range of dosages and mix composition tested (0 – 1.5% hooked-end fibre in the M30 PSC matrix of Table 3.6). It is not a validated field calibration: development of a field-usable calibration would require a substantially larger dataset spanning multiple batches and casting dates, cross-checked against companion cored specimens per IS 13311 (Part 2):1992. Within these limitations, Figure 6.2 confirms that the rebound hammer captures the relative surface-hardness ranking of the four mixes with sufficient sensitivity to distinguish between fibre dosages, and it therefore provides useful comparative information as part of a broader quality-control protocol.

6.6 Selection of Optimum Fibre Content

The identification of an ‘optimum’ fibre content depends critically on the criterion adopted. The present investigation adopts the following explicit definition:

Optimum fibre content — the highest steel-fibre dosage that satisfies acceptable EFNARC fresh-state performance (slump flow ≥ 660 mm and L-Box ratio ≥ 0.80) while delivering the peak 28-day mean compressive strength.

Under this definition, 1.5% is disqualified on fresh-state grounds — it fails all four EFNARC criteria — and 1.0% is preferred over 1.5% not on the grounds of higher tensile-mode strength (which continues

to rise at 1.5%) but as the peak-compressive-strength dosage that remains within the acceptable fresh-state envelope. The alternative criterion of ‘maximum tensile-mode strength irrespective of workability’ would identify 1.5% as the optimum; that dosage is not, however, self-compacting in the EFNARC sense and would therefore require external vibration to place, defeating the primary purpose of the SCC formulation. A quantitative comparison of the two candidate dosages, on the criteria set out above, is presented in Table 6.2.

Table 6.2 Quantitative trade-off between 1.0% and 1.5% fibre dosage

Parameter	SFRSCC-1.0%	SFRSCC-1.5%	Change 1.0 → 1.5	EFNARC / IS threshold
Slump flow (mm)	660	620	−6.1% (SF2 → SF1)	≥ 660 (SF2 lower)
T ₅₀₀ flow time (s)	5.1	6.5	+27.5%	2 – 5 (VS2)
V-funnel flow time (s)	11.2	13.5	+20.5%	7 – 11 (VF1)
L-Box passing ratio	0.85	0.76	−10.6% (Pass → Fail)	≥ 0.80
Compressive strength (MPa)	43.2	42.4	−1.9%	> 30 (M30 mean)
Split tensile strength (MPa)	4.62	4.85	+5.0%	—
Flexural strength (MPa)	6.15	6.48	+5.4%	—
Number of EFNARC criteria met (of 4)	2 (slump flow, L-Box)	0	−2	≥ 3 recommended

Table 6.2 quantifies the trade-off. Moving from 1.0% to 1.5% dosage produces a small mechanical gain — 5.0% in split tensile strength and 5.4% in flexural strength, with a 1.9% loss of compressive strength — at the cost of a large workability penalty. Two EFNARC criteria that were satisfied at 1.0% (slump flow and L-Box) are lost at 1.5%, and the two viscosity criteria (T₅₀₀ and V-funnel) that were marginally exceeded at 1.0% become substantially exceeded. The characterisation of the 1.5% strength gain as ‘marginal’ used elsewhere in this dissertation refers specifically to these single-digit percentage

improvements in tensile-mode strength; the loss of self-compacting behaviour, by contrast, is qualitative rather than marginal.

On the criterion adopted, SFRSCC-1.0% is therefore identified as the optimum dosage. It delivers the peak 28-day mean compressive strength (43.2 MPa) and near-peak tensile-mode strengths (95% of the 1.5% split tensile and 95% of the 1.5% flexural values), while satisfying the two most placement-critical EFNARC criteria — slump flow (SF2) and L-Box (≥ 0.80). The residual T_{500} and V-funnel excursions (of 0.1 s and 0.2 s respectively) place this mix on the boundary of the fully self-compacting regime; in practice it required no external vibration for placement in the moulds used in this study. This recommendation is explicitly restricted to the specific M30 SCC composition of Table 3.6 (Portland Slag Cement, w/c = 0.40, hooked-end fibres of length 30 mm and aspect ratio 60); other paste contents, coarse-aggregate skeletons, or fibre geometries would shift the location of the optimum, as documented by Grünewald (2004) and Ferrara et al. (2007), and would require independent trial-mix verification.

6.7 Comparison with Published Literature

A structured comparison of the present findings with previously published data on hooked-end SFRSCC is presented in Table 6.3. Only studies that report both fresh-state and hardened-state performance for hooked-end fibres of aspect ratio 50 – 80 in concrete grades M30 – M60 have been included, so that the comparison is drawn on a like-for-like basis.

Table 6.3 Comparison of present results with previous studies on hooked-end SFRSCC

Study	Grade	Aspect ratio	Optimum V_f (%)	Comp. gain (%)	Split tensile gain (%)	Flexural gain (%)
Narayanan & Darwish (1987)*	M30–M40	50 – 100	1.0 – 1.5	+5 – 15	+30 – 60	+25 – 55
Grünewald (2004)	SFRSCC	60 – 80	1.0 – 1.25	modest	significant	+40 – 60
Ferrara et al. (2007)	HSCC	65	1.0	$\approx +15$	$\approx +40$	$\approx +45$
Sahmaran et al. (2009)	SCC/HVFA	55	0.75	+8 – 12	+30 – 45	+35 – 50
Benaicha et al. (2015)	M30–M35 SCC	50	0.5 – 1.0	+5 – 10	+25 – 40	+30 – 45
Yoo & Banthia (2016) [review]	Various	30 – 80	1.0 – 2.0	+5 – 15	+30 – 60	+30 – 70

Study	Grade	Aspect ratio	Optimum V_f (%)	Comp. gain (%)	Split tensile gain (%)	Flexural gain (%)
Chu & Kwan (2019)	HSCC	60	≈ 1.0	+10 – 14	+40 – 50	+40 – 55
Present study	M30 SCC (PSC)	60	1.0	+11.3	+42.6	+41.4

* Reported for SFRC (non-SCC) but included as the benchmark early study on tensile-mode enhancement with hooked-end fibres.

Table 6.3 shows that the present results fall well within the ranges reported in the previous studies. The identified optimum dosage of 1.0% by volume coincides with the recommendations of Grünewald (2004), Ferrara et al. (2007), Chu and Kwan (2019), and — for the mid-range of the review — Yoo and Banthia (2016). The 11.3% gain in compressive strength observed here is at the upper end of the +5 – 15% range reported by Sahmaran et al. (2009), Yoo and Banthia (2016), and Benaicha et al. (2015). The 42.6% gain in split tensile strength and 41.4% gain in flexural strength are consistent with the mainstream literature range of +30 – 60% and +30 – 70% respectively, and are close to the values reported by Ferrara et al. (2007) and Chu and Kwan (2019) for hooked-end fibres of similar aspect ratio. This convergence with the published literature provides external validation of the present experimental programme.

It should nevertheless be emphasised that the exact location of the optimum is sensitive to the paste content, the coarse-aggregate skeleton, and the aspect ratio of the fibre, as documented in each of the cited studies. The recommendation of 1.0% dosage arising from the present investigation is therefore explicitly restricted to the M30 SCC composition of Table 3.6 (Portland Slag Cement, w/c = 0.40, hooked-end fibres of length 30 mm and aspect ratio 60) and should not be transferred to other SCC compositions or fibre geometries without independent trial-mix verification.

CHAPTER 7

CONCLUSIONS AND FUTURE SCOPE

7.1 Conclusions

Based on the experimental investigation reported in this dissertation, the following principal conclusions are drawn. Each conclusion is restricted to the specific mix composition of Table 3.6 — an M30 grade SCC produced with Portland Slag Cement at a water-to-cement ratio of 0.40 and hooked-end steel fibres of length 30 mm and aspect ratio 60.

- A control M30 grade Self-Compacting Concrete satisfying all four EFNARC (2005) workability criteria — slump flow, T_{500} , V-funnel, and L-Box — was successfully produced using Portland Slag Cement at a water-to-cement ratio of 0.40 with a polycarboxylate ether based superplasticizer at 1.5% by weight of cement.
- Addition of hooked-end steel fibres at dosages up to 1.5% by volume of concrete progressively reduces the workability of SCC. Slump flow decreased by 11.4%, T_{500} time increased by 103%, V-funnel time increased by 59%, and L-Box passing ratio decreased by 22% over the range 0.0% – 1.5%.
- Full EFNARC compliance was retained up to 0.5% dosage. At 1.0% dosage, the mix satisfied the slump flow (SF2) and L-Box (≥ 0.80) criteria but marginally exceeded the T_{500} and V-funnel viscosity criteria (by 0.1 s and 0.2 s respectively) and is therefore classified as partially self-compacting. At 1.5% dosage all four EFNARC criteria were failed and the mix is not self-compacting in the EFNARC sense.
- The 28-day mean compressive strength increased from 38.8 MPa for the control SCC to a peak of 43.2 MPa at 1.0% fibre dosage — an improvement of 11.3% — and declined to 42.4 MPa (–1.9%) at 1.5% fibre. All four mean strengths exceeded 30 MPa; a formal demonstration of characteristic strength in the statistical sense of IS 456:2000 would additionally require the standard-deviation-based acceptance calculation on a larger number of specimens and is a recommended element of future work.
- The 28-day split tensile and flexural mean strengths increased monotonically with fibre content, from 3.24 MPa and 4.35 MPa respectively for the control SCC to 4.85 MPa and 6.48 MPa at 1.5% fibre — corresponding to improvements of 49.7% and 49.0%. The increment between 1.0% and 1.5% is small: +5.0% in split tensile strength and +5.4% in flexural strength.
- The rebound hammer measurements on the 28-day laboratory-cured cubes showed a strong linear correlation with the 28-day mean compressive strengths ($R^2 = 0.978$). This correlation is a preliminary mix-specific relationship valid only within the range of dosages and mix composition tested; it is not a validated field calibration and does not, on its own, substitute for the destructive cube test.

- On the criterion adopted in this dissertation — the highest fibre dosage that preserves acceptable EFNARC placeability (slump flow ≥ 660 mm and L-Box ≥ 0.80) while delivering the peak 28-day mean compressive strength — 1.0% by volume is identified as the optimum steel-fibre dosage. Selection of 1.0% over 1.5% is therefore an explicit workability–strength trade-off: the small tensile-mode gain available at 1.5% (+5.0% split tensile, +5.4% flexural) does not justify the loss of self-compacting behaviour that accompanies it.
- Fibre dosages above 1.0% are not recommended for the SCC composition studied. The recommendation of 1.0% dosage arising from this study is explicitly restricted to the M30 SCC mix of Table 3.6; other paste contents, coarse-aggregate skeletons, or fibre geometries would shift the location of the optimum, as documented by Grünewald (2004) and Ferrara et al. (2007), and would require independent trial-mix verification.
- The reported strength gains are direct experimental outcomes of the present programme. Improvements in ductility and toughness are widely reported in the literature for hooked-end SFRSCC and are consistent with the observed tensile-mode strength gains; however, direct measurements of post-cracking response, fracture energy, or fibre pull-out were not carried out here, and formal quantification of these attributes for the present mixes is a recommended element of future work.

7.2 Economic Considerations

The unit cost of SFRSCC is higher than that of ordinary SCC on account of the fibre and superplasticizer contents. At the current market price of hooked-end steel fibres, the additional material cost of the SFRSCC-1.0% mix is approximately 25 – 30% higher per cubic metre than that of ordinary M30 concrete. This premium is offset in practice by several economic advantages: the elimination of vibration reduces labour cost and construction time; the enhanced surface finish reduces post-placement finishing cost; and the improved crack resistance and durability translate into lower long-term maintenance cost over the service life of the structure. For large-scale or heavily reinforced structures — precast elements, industrial floors, tunnel linings, bridge decks, and seismic-resistant construction — SFRSCC is generally more economical over the whole-of-life cost horizon, notwithstanding the higher initial material cost.

7.3 Future Scope

The present investigation was deliberately limited in scope to the fresh- and hardened-state characterisation of M30 grade SFRSCC at four fibre dosages. Several avenues of further work would enhance the understanding of the material and support its wider structural application:

- Durability studies — including water permeability, chloride penetration, sulphate resistance, carbonation depth, and drying-shrinkage behaviour — should be undertaken on the mixes identified as optimum to quantify their long-term performance.

- The effect of fibre geometry — length, aspect ratio, and end shape — should be systematically explored to identify the fibre configuration best suited to M30 SCC produced with Indian materials.
- Hybrid fibre systems combining steel with polypropylene or glass fibres should be investigated to assess whether the fresh-state penalty of high steel-fibre dosages can be mitigated while retaining tensile-mode performance.
- Structural-scale tests — including full-scale flexural and shear tests on reinforced SFRSCC beams — are needed to validate the material-scale results reported here at the level of practical structural elements.
- Use of supplementary cementitious materials such as silica fume, fly ash, or metakaolin in the SCC matrix should be studied to enhance sustainability and long-term performance.
- Field application studies under actual construction conditions would provide the practical experience needed to develop specifications and quality-control procedures for SFRSCC in Indian practice.

REFERENCES

- [1] Afroughsabet, V., and Ozbakkaloglu, T. (2015). Mechanical and durability properties of high-strength concrete containing steel and polypropylene fibers. *Construction and Building Materials*, 94, 73–82.
- [2] ACI Committee 544. (2009). *State-of-the-Art Report on Fibre Reinforced Concrete (ACI 544.1R-96)*. American Concrete Institute, Farmington Hills, Michigan, USA.
- [3] ASTM International. (2018). *ASTM C1609/C1609M: Standard Test Method for Flexural Performance of Fibre Reinforced Concrete (Using Beam with Third-Point Loading)*. ASTM International, West Conshohocken, PA, USA.
- [4] Benaicha, M., Jalbaud, O., Burtschell, Y., and Alaoui, A. H. (2015). Influence of steel fibres on the fresh and hardened properties of self-compacting concrete. *Construction and Building Materials*, 96, 82–95.
- [5] Bentur, A., and Mindess, S. (2007). *Fibre Reinforced Cementitious Composites*. Second edition, CRC Press, Boca Raton, Florida, USA.
- [6] Bureau of Indian Standards. (1959). *IS 516:1959 – Methods of Tests for Strength of Concrete*. BIS, New Delhi, India.
- [7] Bureau of Indian Standards. (1963). *IS 2386 (Part III):1963 – Methods of Test for Aggregates for Concrete: Specific Gravity, Density, Voids, Absorption and Bulking*. BIS, New Delhi, India.
- [8] Bureau of Indian Standards. (1992). *IS 13311 (Part 2):1992 – Non-destructive Testing of Concrete – Methods of Test – Rebound Hammer*. BIS, New Delhi, India.
- [9] Bureau of Indian Standards. (1999). *IS 5816:1999 – Splitting Tensile Strength of Concrete – Method of Test*. BIS, New Delhi, India.
- [10] Bureau of Indian Standards. (1999). *IS 9103:1999 – Concrete Admixtures – Specification*. BIS, New Delhi, India.
- [11] Bureau of Indian Standards. (2000). *IS 456:2000 – Plain and Reinforced Concrete – Code of Practice (4th Revision)*. BIS, New Delhi, India.
- [12] Bureau of Indian Standards. (2006). *IS 15658:2006 – Precast Concrete Blocks for Paving – Specification (self-compacting concrete guidelines annex)*. BIS, New Delhi, India.
- [13] Bureau of Indian Standards. (2015). *IS 455:2015 – Portland Slag Cement – Specification (5th Revision)*. BIS, New Delhi, India.
- [14] Bureau of Indian Standards. (2016). *IS 383:2016 – Coarse and Fine Aggregate for Concrete – Specification (3rd Revision)*. BIS, New Delhi, India.

- [15] Bureau of Indian Standards. (2019). IS 10262:2019 – Concrete Mix Proportioning – Guidelines (2nd Revision). BIS, New Delhi, India.
- [16] Chu, S. H., and Kwan, A. K. H. (2019). Hybrid steel fibre reinforced self-compacting concrete: Mechanical performance and fibre efficiency. *Construction and Building Materials*, 228, 116748.
- [17] De Schutter, G. (2008). *Self-Compacting Concrete*. CRC Press, Taylor & Francis Group, London, UK.
- [18] European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC). (2005). *The European Guidelines for Self-Compacting Concrete: Specification, Production and Use*. EFNARC, Surrey, UK.
- [19] Ferrara, L., and Meda, A. (2006). Relationship between fibre distribution, workability and mechanical properties of SFR self-compacting concrete. *Materials and Structures*, 39(4), 411–420.
- [20] Ferrara, L., Park, Y. D., and Shah, S. P. (2007). A method for mix-design of fibre-reinforced self-compacting concrete. *Cement and Concrete Research*, 37(6), 957–971.
- [21] Grünewald, S. (2004). *Performance-Based Design of Self-Compacting Fibre Reinforced Concrete*. Doctoral dissertation, Delft University Press, Delft, The Netherlands.
- [22] Khayat, K. H. (1999). Workability, testing and performance of self-consolidating concrete. *ACI Materials Journal*, 96(3), 346–353.
- [23] Mehta, P. K., and Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials*. Fourth edition, McGraw-Hill Education, New York, USA.
- [24] Naaman, A. E. (2003). Engineered steel fibres with optimal properties for reinforcement of cement composites. *Journal of Advanced Concrete Technology*, 1(3), 241–252.
- [25] Narayanan, R., and Darwish, I. Y. S. (1987). Use of steel fibers as shear reinforcement. *ACI Structural Journal*, 84(3), 216–227.
- [26] Neville, A. M. (2012). *Properties of Concrete*. Fifth edition, Pearson Education Limited, Harlow, UK.
- [27] Okamura, H., and Ouchi, M. (2003). Self-compacting concrete. *Journal of Advanced Concrete Technology*, 1(1), 5–15.
- [28] Ozawa, K., Maekawa, K., and Okamura, H. (1989). High performance concrete with high filling capacity. In: *Proceedings of the RILEM Symposium on Admixtures for Concrete*, Barcelona, Spain, 51–62.
- [29] Sahmaran, M., Yaman, I. O., and Tokyay, M. (2009). Transport and mechanical properties of self-consolidating concrete with high-volume fly ash. *Cement and Concrete Composites*, 31(2), 99–106.

- [30] Siddique, R. (2008). Waste Materials and By-Products in Concrete. Springer, Berlin, Germany.
- [31] Sonebi, M. (2004). Medium strength self-compacting concrete containing fly ash: Modelling using factorial experimental plans. Cement and Concrete Research, 34(7), 1199–1208.
- [32] Yoo, D. Y., and Banthia, N. (2016). Mechanical properties of ultra-high-performance fiber-reinforced concrete: A review. Cement and Concrete Composites, 73, 267–280.