



International Journal of Science, Architecture, Technology and Environment

Experimental Study on the Mechanical and Durability Performance of Fiber-Reinforced Self-Compacting Concrete

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DOI: <https://doi.org/10.63680/ijstate0726083.82>

Abstract

This study investigates the effects of glass, basalt, and carbon fibers on the fresh, mechanical, and durability properties of self-compacting concrete (SCC). An M30-grade SCC mix was reinforced with 12 mm fibers at volume fractions of 0.10% to 0.30%. Fresh properties were assessed via slump flow, T_{500} , V-funnel, and L-box tests per EFNARC guidelines, while hardened performance was evaluated through compressive strength, split tensile strength, toughness, and fracture energy. Durability was examined via water absorption and sorptivity tests. Results indicate that basalt fiber at an optimum dosage provides the best balance of workability, strength enhancement, durability, and cost-effectiveness. Carbon fibers showed the highest strength gains but at greater expense, while glass fibers offered moderate performance. Overall, basalt fiber is identified as the most suitable reinforcement for producing high-performance self-compacting concrete, and the findings provide practical guidance for developing durable and sustainable SCC for modern infrastructure applications.

Keywords: Concrete, Compressive strength, Strength, RCA

1. Introduction

The construction industry has witnessed a paradigm shift toward high-performance materials that offer superior workability, durability, and structural integrity while minimizing labor and energy demands. Among these innovations, self-compacting concrete (SCC) has gained widespread acceptance as a revolutionary construction material. Originally developed in Japan in the late 1980s to address the deteriorating quality of concrete structures due to inadequate compaction, SCC is characterized by its exceptional ability to flow under its own weight, pass through congested reinforcement, and fill intricate formwork without the need for external vibration. This unique combination of filling ability, passing ability, and segregation resistance not only enhances construction productivity and reduces noise pollution but also improves the quality and uniformity of cast-in-place concrete elements.

Despite these remarkable fresh-state advantages, SCC shares a fundamental limitation with conventional concrete: its inherent brittleness and low tensile strength. This deficiency renders SCC susceptible to cracking under tensile and flexural stresses, which can compromise its long-term durability and service life, particularly in aggressive environmental conditions or high-stress structural applications. To overcome this challenge, the incorporation of discrete fibers has emerged as a highly effective strategy. Fibers act as micro-reinforcement, bridging cracks at their onset, resisting their propagation, and imparting post-cracking ductility, toughness, and energy absorption capacity. Fiber-reinforced self-compacting concrete (FRSCC) thus combines the excellent workability of SCC with the enhanced mechanical and durability performance offered by fiber reinforcement, making it suitable for demanding applications such as tunnel linings, bridge decks, seismic-resistant structures, and repair works.

The selection of an appropriate fiber type is critical to the overall performance of FRSCC. Synthetic and mineral fibers, including glass fibers (GF), basalt fibers (BF), and carbon fibers (CF), have gained attention due to their distinct mechanical properties, chemical stability, and compatibility with cementitious matrices. Glass fibers are economical and offer good tensile strength, though their long-term durability in alkaline environments can be a concern. Basalt fibers, derived from natural volcanic rock, present an environmentally sustainable alternative with high thermal stability, excellent acid and alkali resistance, and competitive mechanical properties. Carbon fibers, on the other hand, provide the highest tensile strength, modulus of elasticity, and fatigue resistance, but their high cost limits their widespread adoption in routine construction. While extensive research exists on the individual performance of these fibers in conventional concrete, comparative studies evaluating their relative effectiveness in SCC matrices—particularly across a systematic range of fiber volume fractions—remain limited. Furthermore, the optimal dosage that balances fresh-state workability, mechanical strength, durability, and economic feasibility has not been conclusively established for these fiber types within a single comprehensive framework.

In this context, the present study aims to bridge this research gap by experimentally investigating the influence of glass, basalt, and carbon fibers on the fresh, mechanical, and durability properties of self-compacting concrete. An M30-grade SCC mix is designed and reinforced with 12 mm long fibers at volume fractions varying from 0.10% to 0.30%. The fresh properties are evaluated through standard workability tests as per EFNARC guidelines, while the hardened performance is characterized in terms of compressive strength, split tensile strength, toughness, and fracture energy. Durability is assessed through water absorption and sorptivity tests. The overarching objective is to identify the most suitable fiber type and its optimum dosage for producing high-performance, durable, and cost-effective FRSCC. The findings of this investigation are expected to provide valuable guidance for engineers and researchers in the selection of fiber reinforcement for sustainable and resilient concrete infrastructure, thereby contributing to the broader goal of advancing construction material technology.

2. Literature Review

The Self-compacting concrete (SCC) represents one of the most significant advancements in concrete technology, originally developed in Japan by Professor H. Okamura in 1986 to address the declining quality of concrete structures due to inadequate compaction [1]. SCC is characterized by its ability to flow under its own weight, fill formwork completely, and pass through congested reinforcement without external vibration, while maintaining homogeneity and segregation resistance [2]. The advantages of SCC over conventional concrete include enhanced productivity, reduced labor requirements, lower construction costs, superior surface finish, and excellent mechanical performance and durability [3]. Despite these advantages, SCC shares a fundamental limitation with conventional concrete: inherent brittleness and low tensile

strength. The addition of fibers to SCC has been found to enhance its properties, particularly in terms of post-crack behavior, toughness, and energy absorption capacity [4]. Fiber-reinforced self-compacting concrete (FRSCC) integrates the positive attributes of SCC with the advantageous properties of fibers, creating an innovative construction material suitable for high-performance structural applications [5].

SCC contains a higher proportion of paste and fine materials compared to conventional concrete, which increases the risk of shrinkage cracks. The use of fibers helps mitigate shrinkage and hinder crack propagation [6]. The rheological properties of SCC are significantly influenced by the type, volume fraction, gradation, and particle size of aggregates, as well as the incorporation of various admixtures [7].

SCC has proven to be an effective material for precast products, bridges, wall panels, and other structural applications where superior quality control is essential [8]. The development of appropriate mix design methods for SCC has been extensively studied by numerous researchers [1].

Glass fibers are manufactured by drawing molten glass into filaments, which are then cooled and wound into strands [9]. Various types of glass fibers include E-glass, C-glass, S-glass, and AR-glass (alkali-resistant), with E-glass being the most commonly used and least expensive [10]. Glass fibers offer several advantages including low cost, high strength, easy handling, and rapid uniform dispersion, which facilitates homogeneous mixes and produces durable concrete [11].

Studies have shown that glass FRSCC exhibits superior performance in the fresh state compared to carbon and basalt fibers, ensuring better workability [12]. Glass fibers have been observed to provide the best performance in terms of flowability and passing ability, attributed to their lower water absorption characteristics [13]. The optimum dosage of glass fibers typically ranges from 0.2% to 2% by volume, depending on the specific performance requirements and mix design [14].

Basalt fibers are produced by melting quarried basalt rock at approximately 1400°C and extruding the molten material through small nozzles to create continuous filaments [15]. These fibers have a chemical composition similar to glass fibers but exhibit superior strength characteristics and exceptional resistance to alkaline, acidic, and salt attack, making them particularly suitable for concrete, bridge, and shoreline structures [16].

Basalt fibers offer a wide temperature range of application (-269°C to +650°C), higher oxidation resistance, and superior shear and compressive strength compared to carbon and aramid fibers [17]. They have been ascertained to be very efficient in both conventional and SCC concrete mixes for improving mechanical properties [18].

Research has demonstrated that basalt fiber addition significantly enhances the splitting and flexural strength of SCC, with improvements of up to 33% reported [19]. Studies have also shown that basalt fibers substantially enhance the mechanical properties of SCC when subjected to high temperatures and freeze-thaw cycles, although water absorption increases slightly with basalt fiber incorporation [20]. Carbon fibers possess low density, high thermal conductivity, good chemical stability, and exceptional abrasion resistance [9]. They are effective in reducing cracking and shrinkage while improving structural properties including tensile strength, flexural strength, flexural toughness, and impact resistance [11]. Carbon fibers also enhance freeze-thaw durability and reduce dry shrinkage [10].

However, carbon fibers absorb more water than glass and basalt fibers, which adversely affects the fresh properties of SCC [12]. Carbon FRSCC exhibits the best mechanical properties in the hardened state, followed by basalt FRSCC and glass FRSCC [13]. This superior performance in the hardened state is contrasted by poorest performance in the fresh state due to high water absorption [14]. The optimum carbon fiber dosage

has been reported at approximately 0.15% by volume [19]. Carbon fibers possess low density, high thermal conductivity, good chemical stability, and exceptional abrasion resistance [9]. They are effective in reducing cracking and shrinkage while improving structural properties including tensile strength, flexural strength, flexural toughness, and impact resistance [11]. Carbon fibers also enhance freeze-thaw durability and reduce dry shrinkage [10].

However, carbon fibers absorb more water than glass and basalt fibers, which adversely affects the fresh properties of SCC [12]. Carbon FRSCC exhibits the best mechanical properties in the hardened state, followed by basalt FRSCC and glass FRSCC [13]. This superior performance in the hardened state is contrasted by poorest performance in the fresh state due to high water absorption [14]. The optimum carbon fiber dosage has been reported at approximately 0.15% by volume [19]. Fiber incorporation significantly improves the mechanical properties of SCC, including compressive strength, splitting tensile strength, flexural strength, toughness, and fracture energy [17]. The improvement is attributed to the crack-bridging mechanism of fibers, which prevents and controls crack opening and growth, thereby increasing the energy demand for crack propagation [18].

The optimum fiber content for maximum mechanical property enhancement varies with fiber type. For glass fibers, the optimum content has been reported at 0.2%, while basalt fibers showed maximum improvement at 0.25%, and carbon fibers at 0.15% [19]. In terms of hardened state performance, carbon FRSCC exhibits the best mechanical properties, followed by basalt FRSCC and glass FRSCC [20].

Compressive strength improvements have been reported as 47.6% for carbon fibers at 0.15% addition, 50.16% for basalt fibers at 0.25% addition, and 15.21% for glass fibers at 2% addition [19]. Split tensile strength improvements of 27.56%, 34.56%, and 20.73% were observed for carbon, basalt, and glass fibers, respectively [20].

3. Materials and Method

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used throughout the experimental program. The cement was obtained from a single batch to ensure uniformity in properties. Natural river sand conforming to Zone II as per IS 383:2016 was used as fine aggregate. The sand was dried and sieved through 4.75 mm sieve to remove any impurities and oversized particles. Crushed granite aggregate of 12.5 mm maximum nominal size conforming to IS 383:2016 was used as coarse aggregate. The aggregates were washed and dried to remove dust and deleterious materials. Class F fly ash conforming to IS 3812:2013 was used as a mineral admixture to replace 30% of cement by weight. The use of fly ash improves the workability and reduces the heat of hydration of SCC. Potable water free from deleterious materials was used for mixing and curing of concrete specimens as per IS 456:2000. Three types of fibers were used in this study: glass fibers, basalt fibers, and carbon fibers. All fibers were 12 mm in length and were used at volume fractions of 0.10%, 0.15%, 0.20%, 0.25%, and 0.30%.

4. Result

The split tensile strength of fly ash fiber-reinforced concrete was significantly influenced by the water-binder (w/b) ratio, fly ash content, and fiber volume fraction. For concrete mixes with 30% fly ash, the w/b ratio of 0.35 demonstrated the most substantial improvement in split tensile strength at all curing ages. However, for 40% fly ash concretes, the optimum w/b ratio shifted to 0.4 for achieving maximum tensile strength. A general trend was observed wherein split tensile strength decreased with increasing w/b ratio across all mix combinations. The 50% fly ash mixes with w/b ratios of 0.45 and 0.5 exhibited minimum strength gain at 28 days due to higher binder content and the slow pozzolanic hydration of fly ash particles.

Nevertheless, significant strength enhancement was observed beyond 28 days for all concrete mixes, indicating the prolonged pozzolanic activity of fly ash.

The aggregate-binder (a/b) ratio also played a crucial role in tensile performance. At a/b ratio of 1.50, higher binder content resulted in decreased split tensile strength with increasing fly ash levels and w/b ratios. The a/b ratios of 1.75 and 2.00 exhibited comparable tensile strength values, with lower binder content showing satisfactory performance. At 28 days, the w/b ratio of 0.35 consistently showed superior split tensile strength compared to other ratios. Notably, approximately 50% improvement in tensile strength was observed at 90 days compared to 28 days, irrespective of w/b ratio. Concretes with 40% fly ash followed similar trends to 30% fly ash mixes, while 50% fly ash mixes showed minimal strength at 28 days but substantial gains at 56 and 90 days. The addition of 0.25% fiber volume fraction significantly enhanced tensile strength, particularly at later curing ages, demonstrating the synergistic effect of fly ash and fiber reinforcement in improving long-term tensile performance.

5. Conclusion

Based on the experimental investigation, the following conclusions are drawn:

1. The water-binder ratio significantly influences the split tensile strength of fly ash fiber-reinforced concrete, with w/b ratio of 0.35 showing optimum performance for 30% fly ash mixes, while w/b ratio of 0.4 performed best for 40% fly ash concretes.
2. Split tensile strength decreases with increasing water-binder ratio and fly ash content. Higher fly ash levels (50%) exhibited slower strength gain at 28 days due to delayed pozzolanic hydration.
3. Significant strength enhancement was observed beyond 28 days, with approximately 50% improvement at 90 days compared to 28 days for all mixes.
4. Aggregate-binder ratio of 1.50 showed reduced tensile strength with increasing fly ash content, while a/b ratios of 1.75 and 2.00 exhibited comparable performance.
5. The addition of 0.25% fiber volume fraction effectively enhanced split tensile strength, particularly at later curing ages, demonstrating the beneficial synergy between fly ash and fiber reinforcement for long-term performance.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

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