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Advancements in Concrete Technology: A Comprehensive Review of Steel Fiber Reinforcement

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A B S T R A C T

Concrete is inherently brittle with a limited strain capacity under tensile stress. To improve its mechanical performance, steel fibers are incorporated, as they have been proven to enhance ductility and increase energy dissipation capacity (1–5). Steel fibers act as a bridging mechanism for crack transfer, mitigating crack propagation and restricting further widening. Owing to these advantages, extensive research has demonstrated that incorporating fibers into concrete mixtures significantly enhances overall performance compared to conventional concrete. However, while steel fiber reinforcement improves tensile strength and post-cracking behavior, its contribution to compressive strength enhancement remains minimal (6). This paper explores the effects of steel fiber addition in concrete, its mixing process, and the mechanical properties of SFRC based on previous studies.

Keywords: Reinforced Concrete, Steel Fiber, Crack Resistance, Ductility

Introduction

The use of fiber-reinforced composites dates back to the Roman period (300 BC – 476 BC) or approximately 10,000 years ago, as evidenced by the discovery of mud bricks reinforced with straw at several ancient Middle Eastern sites. These findings suggest the early development of fiber-reinforced concrete. Over time, advancements in the material led to the first official patent for fiber-reinforced concrete by A. Bernard in California in 1874. However, its widespread implementation remained limited due to high production costs and inadequate infrastructure. It was not until 1962 that James Romualdi conducted pioneering research, providing a more comprehensive understanding of Steel Fiber Reinforced Concrete (SFRC) and its mechanical behavior (5).

Concrete is inherently a brittle material with limited strain capacity under tensile stress. To enhance its mechanical properties, steel fibers are incorporated, as they have been demonstrated to improve ductility and increase energy dissipation capacity (1–5). Steel fiber is considered a highly promising reinforcement material for concrete due to its numerous advantages. Globally, over 0.3 million tons of steel fibers are produced and commercially distributed each year, with an estimated annual growth rate of 20% (7–9). However, steel fibers cannot serve as a direct substitute for conventional reinforcing steel. This paper investigates the influence of steel fiber incorporation in concrete, its mixing methodology, and the mechanical properties of steel fiber-reinforced concrete based on findings from previous studies.

Steel Fiber Reinforced Concrete (SRFC)

Based on ACI 544.3R-93 (6), Steel Fiber Reinforced Concrete (SFRC) is defined as a composite material consisting of hydraulic cement, a combination of coarse and fine aggregates, and randomly dispersed steel fibers within a discontinuous matrix. Steel fibers function as a bridging mechanism that transfers cracks from one side to another, thereby preventing further crack propagation and widening (10,11). Extensive research has demonstrated that incorporating fibers into concrete mixtures significantly enhances performance, including improvements in tensile strength, flexural strength, and energy dissipation, compared to conventional concrete (7,12–15).

The ability of fiber-reinforced concrete to enhance mechanical performance has led researchers to integrate it with the characteristics of Self-Compacting Concrete (SCC). Nis A., 2018 (16) conducted a study on self-compacting steel fiber-reinforced concrete, highlighting its advantages in time and cost efficiency, particularly in construction applications. Steel fiber-reinforced concrete is increasingly being utilized in critical structural applications (17) and has been developed for various construction purposes, including rigid pavement layers, structural repairs, and precast elements (18).

Mixed Material of SFRC

Han J. et al. 2019 (19) investigated the influence of steel fiber length and the maximum size of coarse aggregate in Steel Fiber Reinforced Concrete (SFRC). The study utilized Chinese standard Portland cement with natural sand of 4.75 mm in size. Coarse aggregate sizes varied from 10 mm, 20 mm, 30 mm, to 40 mm, while steel fiber lengths ranged from 30 mm, 40 mm, 50 mm, to 60 mm. All fibers had a hooked-end shape, a volume fraction of 1%, and length-to-diameter ratios of 0.33 and 0.58. A superplasticizer dosage of 1% by concrete volume was also incorporated. The results indicated that neither the maximum size of coarse aggregate nor the steel fiber length significantly affected the compressive strength of concrete. However, tensile and flexural strengths showed improvement when the maximum aggregate size was 20 mm. The optimal steel fiber length-to-aggregate size ratio for enhanced tensile and flexural performance was determined to be within the range of 1.25 to 3.

However, an increase in the maximum aggregate size negatively impacts the ductility of concrete, as flexural performance declines due to the restricted space available for fiber rotation (11). This observation aligns with Jang S.J. et al., 2017 (20), who investigated the effects of maximum aggregate size and steel fiber volume fraction. Their study concluded that a smaller maximum aggregate size, when combined with a higher fiber volume fraction, significantly enhances flexural performance.

Furthermore, Wu Z. et al., 2016 (21), The study examined the influence of different steel fiber shapes, including straight, wavy, and bent-end fibers, as well as varying steel fiber volume fractions of 0.1%, 2%, and 3%. According to the research findings presented in **Fig. 1**, straight steel fibers exhibited the lowest compressive and flexural strength, whereas the highest values were achieved with bent-end steel fibers at a 3% volume fraction. Among the various fiber types, hooked steel fibers are the most recommended due to their superior performance in enhancing ductility (4,21). Strength improvements using hooked fibers can be up to 3–7 times greater compared to straight fibers (22). In general, the volume fraction of steel fibers ranges from 0.25% to 2%, equivalent to approximately 20–157 kg/m³ (6).

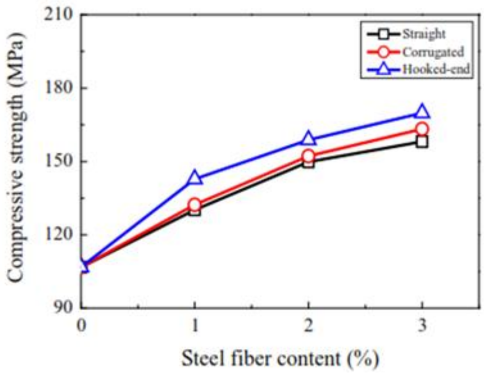

Figure 1. Effect of shape and steel fiber content on concrete compressive strength (Source: Journal of Effects of Steel Fiber Content And Shape on Mechanical Properties of Ultra-High-Performance Concrete, 2016)

On the other hand, compared to synthetic fibers, short steel fibers that are well-separated and evenly distributed are more effective in enhancing the brittleness resistance of concrete. As shown in Fig. 2, steel fibers are randomly dispersed around the coarse aggregate within the concrete mix, functioning as a binder (5). Despite this random distribution, it is crucial to ensure uniform dispersion of steel fibers throughout the mixture. To achieve this, the Chinese Construction Industry Standard recommends that the maximum size of coarse aggregate should be limited to 0.5–0.75 times the length of the steel fibers or a maximum of 25 mm (19).

Figure 2. Steel fiber distribution in concrete mixes (Source: Journal Of Steel Fiber Reinforced Concrete Behaviour, Modelling And Design, 2017)

According to ACI 544.3R-93 (6), The typical water-cement (w/c) ratio for steel fiber-reinforced concrete mixtures ranges from 0.35 to 0.50. However, for specialized applications requiring higher quality, a lower w/c ratio between 0.35 and 0.43 is commonly used (4,6,10). Ghasemi M. et.al., 2019 (11) conducted a study on self-compacting concrete reinforced with steel fibers, considering the w/c ratio as a variable with values of 0.42, 0.52, and 0.62. The findings revealed that a lower w/c ratio significantly improves the ductility of concrete.

Mixing Method of SFRC

The selection of mixing equipment significantly influences the quality of Steel Fiber Reinforced Concrete (SFRC). When using a conventional mixer, compressive strength increases by approximately 12%, whereas a vertical planetary mixer yields a greater improvement of up to 20% (9). In the SFRC mixing process, dry materials are initially mixed manually before being blended in a mixer until a homogeneous consistency is achieved (4,5,7). Steel fibers are introduced during the final stage of mixing to prevent fiber clumping. Additionally, a low water-cement (w/c) ratio can hinder the attainment of a uniform mix. Therefore, increasing the mixing speed is crucial to ensuring even fiber distribution and breaking up any residual material clumps (6).

However, in a study by Singh H., 2017 (5), the mixing process for Steel Fiber Reinforced Concrete (SFRC) followed a specific sequence to ensure uniform dispersion of steel fibers. Initially, coarse and fine aggregates were mixed for one minute in the mixer, after which cement and steel fibers were gradually introduced and stirred for an additional minute to promote even fiber distribution. Once the dry materials were thoroughly blended, 80–90% of the total water was added and mixed for two minutes. Subsequently, the superplasticizer and the remaining water were incorporated, followed by an additional mixing period of 3–5 minutes to achieve a homogeneous and well-integrated concrete mixture.

On the other hand, Abbas W. et.al., 2018 (4) employed a different mixing approach, where the superplasticizer was pre-mixed with water before being introduced into the mixer. The mixture was then stirred for three minutes, allowed to rest for three minutes, and subsequently mixed again for an additional two minutes. Steel fibers were added at the final stage of mixing, followed by continuous stirring for five minutes to ensure uniform fiber dispersion throughout the concrete mixture.

An effective mixing method, as proposed by Wang S. et al., 2022 (23) involves initially blending dry materials, including the cement binder, coarse aggregate, and fine aggregate, for 2–3 minutes. Subsequently, 75% of the total water, pre-mixed with a superplasticizer, is gradually introduced into the dry mixture and stirred for 3–4 minutes. The remaining water and steel fibers are then added in the final stage and mixed for an additional 2–3 minutes to ensure uniform dispersion and a homogeneous concrete mix

A similar mixing method was implemented in Indonesia by Oesman M. et al., 2022 (24). The process began with the mixing of dry materials, including supplementary cementitious materials (SCM), cement, crushed stone, and natural sand, for two minutes. Then, 90% of the total water, pre-mixed with a superplasticizer, was gradually introduced and stirred for four minutes. Once the mixture attained a paste-like consistency, the mixing speed was increased for one minute. The remaining water and steel fibers were then gradually incorporated and mixed for an additional four minutes until a homogeneous consistency was achieved, followed by a final one-minute increase in mixing speed to ensure uniform dispersion of the fibers.

Workability of SFRC

In fibrous concrete, the use of hooked-end steel fibers is recommended, as discussed in Section 2. However, Han J. et al. (2019) (19) highlighted that hooked-end steel fibers negatively impact the flowability of fresh concrete due to the formation of a cementitious network that encases the fibers, restricting the movement of the mixture. A similar observation was reported by Wu et al. (2016) (21) who compared the effects of straight, wavy, and hooked-end steel fibers on the flowability of fresh concrete. As illustrated in Fig. 3, straight steel fibers exhibited the highest flowability, followed by wavy steel fibers, while hooked-end steel fibers showed the lowest flowability. Furthermore, the study indicated that flowability decreases as the steel fiber volume fraction increases, with reductions of 20.9%, 35.8%, and 51.2% for volume fractions of 1%, 2%, and 3%, respectively

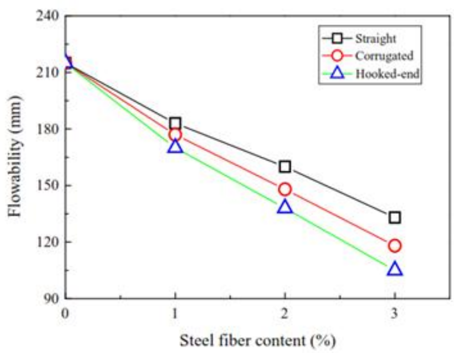

Figure 3. Effect of shape and steel fiber content on the flowability of fresh concrete (Source: Journal of Effects of Steel Fiber Content And Shape on Mechanical Properties of Ultra-High-Performance Concrete, 2016)

A similar conclusion was drawn in the study by Wang S. et al. (2022) (23), as shown in **Fig. 4**, where the flowability of fresh concrete decreased with an increase in fiber content from 1.5% to 3%. The test samples R15, R17, and R19 contained water-cement (w/c) ratios of 0.15, 0.17, and 0.19, respectively. Based on the test results, it was evident that workability and the w/c ratio are directly proportional—higher w/c ratios resulted in increased flowability of the fresh concrete mixture.

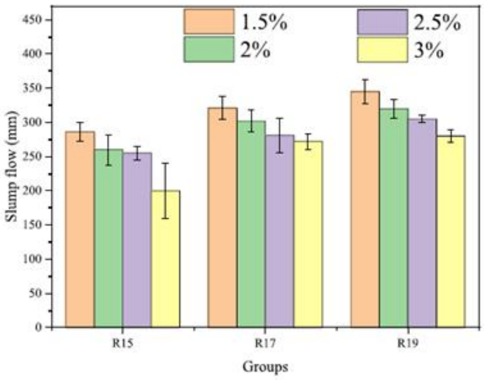

Figure 4. Workability of each sample (Source: Journal of Effects of Steel Fibers And Concrete Strength on Flexural Tougness of Ultra-High Performance Concrete With Coarse Aggregate, 2022)

In addition, an increase in the maximum coarse aggregate size in the concrete mix reduces the proportion of smaller particles in the aggregate, thereby decreasing the specific surface area. This reduction in surface area affects the slump of fresh concrete. In this context, as the coarse aggregate size increases, the slump of fresh concrete also tends to increase due to the reduced surface area requiring less binder to coat the aggregate particles.

Mechanical Properties of SFRC

The addition of fibers in concrete significantly enhances the compressive strain at ultimate load; however, it has a minimal effect on compressive strength (6,25). The compressive strength showed only a slight increase of approximately 2–8% with fiber content ranging from 0.5% to 1.5% over a 28-day curing period (10). Key factors that can significantly improve the compressive strength of self-compacting concrete include the use of finely powdered materials and a low water-cement (w/c) ratio (14,26). In a separate study, a notable improvement in tensile capacity was observed with the addition of steel fibers in concrete, showing a 31% increase at low w/c ratios and a 47% increase at higher w/c ratios (4). Furthermore, increasing the steel fiber content from 20 kg/m³ to 80 kg/m³ resulted in a 44.62% enhancement in split tensile strength (27).

Compared to conventional concrete, steel fiber-reinforced concrete (SFRC) demonstrates superior post-cracking behavior and enhanced crack resistance (9,28). Wu Z. et al., (2016) (21) supported this claim, stating that while steel fibers have a minimal impact on the load-deflection curve before cracking occurs, they play a significant role in the post-cracking phase.

Several factors influence the post-cracking strength of SFRC, including the properties of the steel fibers—such as material composition, shape, and aspect ratio. Additionally, the volume fraction of steel fibers and the characteristics of the concrete matrix also contribute to post-cracking strength (29). This improvement is attributed to the fibers' ability to resist loads through mechanical interlocking and frictional resistance at the fiber-matrix interface (12).

Conclusion

Steel Fiber Reinforced Concrete (SFRC) is a composite material that integrates steel fibers into the concrete mix, enhancing its mechanical properties and overall structural performance. The inclusion of steel fibers significantly increases toughness, ductility, and energy dissipation capacity compared to conventional concrete, making it highly suitable for various construction applications. However, to maximize the benefits of SFRC, careful attention must be given to factors such as the mixing process, fiber characteristics, and aggregate size. Key considerations in optimizing SFRC performance include:

Composition and properties: Steel Fiber Reinforced Concrete (SFRC) is composed of hydraulic cement combined with coarse and fine aggregates, along with steel fibers that serve as crack control mechanisms. These fibers effectively hinder crack propagation, thereby enhancing the material's durability, toughness, and structural integrity.

Characteristics of steel fibers: The characteristics of steel fibers—such as shape, aspect ratio, and volume fraction—play a crucial role in the post-cracking behavior of SFRC. A well-designed fiber blend enhances bonding and friction within the cement matrix, leading to improved mechanical performance. For optimal results in enhancing ductility, the use of twisted-tip steel fibers is recommended, as they provide superior anchorage and crack-bridging capabilities.

Water-cement ratio (w/c): A lower water-cement (w/c) ratio enhances the overall quality and strength of concrete, improving its durability and mechanical properties. However, it also reduces the flowability of fresh concrete, making workability more challenging. To counteract this issue, the use of superplasticizers is often necessary to achieve a balance between high strength and adequate flowability

Maximum aggregate size and fiber length: The size of coarse aggregates and the length of steel fibers have minimal impact on the compressive strength of SFRC. However, they play a significant role in enhancing tensile and flexural strengths by improving crack resistance and energy dissipation.

Optimizing the aggregate size and fiber length ratio is essential for achieving better mechanical performance, particularly in applications requiring high tensile and flexural capacity

Mixing method: Achieving uniform fiber distribution in SFRC requires an appropriate mixing technique. Increasing the mixing speed is essential to ensure even fiber dispersion and to break up any clumps in the mixture. A planetary mixer is recommended over a conventional mixer due to its superior ability to achieve a more homogeneous mix. The mixing process typically involves:

Dry Mixing Stage: Coarse and fine aggregates, cement, and supplementary materials are blended first.

Gradual Liquid Addition: Water and superplasticizer are introduced gradually while mixing continues.

Final Stage: Steel fibers and the remaining liquid solution are added, ensuring proper dispersion and preventing fiber clumping.

This method enhances the workability and mechanical performance of SFRC while maintaining consistency in fiber distribution.

Mechanical properties: While the incorporation of steel fibers significantly enhances the tensile and flexural strength of SFRC, its effect on compressive strength remains minimal, with only a slight increase observed. This is primarily due to the role of fibers in crack control rather than load-bearing capacity under compression.

Continued research and development in this field will lead to further advancements in fiber optimization, mix design, and application techniques, ultimately expanding the potential of steel fiber-reinforced concrete in modern construction.

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