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Influence of Extra-Short Extra-Fine Steel Fibers on Mechanical Properties of Self-Compacting Concrete with Single-Doped Fly Ash

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Abstract: This study assesses the influence of extra-short extra-fine steel fibers on the performance of self-compacting concrete (SCC) modified with fly ash. Replacing standard steel fibers with volume fractions ranging from 0%, 1.5%, 3%, 5% and 6%, the study optimizes the mix design for enhanced workability and mechanical properties. The findings reveal that, although the addition of steel fibers had a negative effect on the flowability, the cohesion is significantly improved, providing a basis for a significant improvement in the mechanical properties. The optimal fiber content is identified at 5%, achieving the highest compressive strength of 71.7 MPa, split tensile strength of 8.2 MPa, and flexural strength of 12.8 MPa at 28 d. However, further increases in fiber content beyond 5% lead to a deceleration in compressive and splitting tensile strength improvement and a 27.5% drop in flexural strength at 28 d. The study also emphasizes the good dispersion within the concrete, which helps to enhance its ductility and crack resistance, to some extent.

Keywords: fly ash; self-compacting concrete; extra-short extra-fine steel fiber; mechanical properties

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1. Introduction

Self-compacting concrete (SCC) represents an innovative class of concrete that possesses inherent self-compacting properties and enhanced impermeability, which has led to its extensive utilization within the engineering sector. The primary distinctions between self-compacting concrete and traditional concrete are predominantly evident in their construction applications. Specifically, the mix proportion of SCC must be meticulously adjusted to account for various factors, including the structural composition of the environment and the specific construction techniques employed. To achieve the desired performance, SCC demands superior cohesiveness and fluidity, necessitating the use of higher-quality ingredients such as cementitious materials, sand, and aggregates, as well as admixtures, in comparison to those used in ordinary concrete formulations [1]. The addition of steel fibers to self-compacting concrete enhances its tensile strength, impact resistance, and durability. When sourced from recycled materials, the addition of steel fibers contributes to environmentally friendly construction practices [2]. Fly ash is a typical concrete admixture that can improve the workability, durability, and environmental friendliness of concrete. For example, in geopolymer concrete (GPC), fly ash is an important binder as a waste material [3]. Extensive research has explored the integration of fly ash in GPC. These studies collectively highlight fly ash's role in enhancing the concrete industry's environmental sustainability and material performance [4–6]. Therefore, it is of great theoretical and practical significance to study the influence of fly ash on the mechanical properties of self-compacting concrete with steel fibers.

Self-compacting concrete is distinguished from conventional concrete through several key aspects, including the selection of raw materials, the design of the concrete mix, the implementation of quality control measures, and the execution of performance-testing protocols. The superior performance characteristics of SCC are significantly influenced by the incorporation of mineral admixtures such as fly ash, silica fume, and the judicious selection of aggregates. Additionally, the use of water-reducing agents plays a pivotal role in enhancing the workability and rheological properties of SCC, thereby facilitating its self-compacting capabilities. These additives not only contribute to the improved fluidity and cohesiveness of the concrete but also have a profound impact on its overall performance in various construction applications [7–9]. The utilization of mineral admixtures in the production of SCC is a critical component, with the optimal replacement ratio of these admixtures for cement ranging between 25% and 35%. It has been established that deviations from this range, either through insufficient or excessive inclusion, can adversely impact the workability and mechanical properties of the concrete. Fly ash, in particular, is recognized as an environmentally sustainable material that is indispensable to the concrete manufacturing process. It exerts a trifecta of beneficial effects on the concrete: it enhances the concrete's impermeability, bolsters its late-stage strength, and contributes to the maintenance of the concrete's volume stability. Furthermore, fly ash is instrumental in reducing the heat generated during the hydration process of mass concrete, thereby mitigating the risk of thermal cracking. The judicious use of fly ash, therefore, not only promotes sustainability but also significantly enhances the performance and longevity of concrete structures.

A comprehensive body of research has explored the influence of mineral admixtures, specifically fly ash (FA), on the mechanical and durability characteristics of self-compacting concrete (SCC) when used as a substitute for cement. Çelik et al. [10] and Kumar and Rai [11] conducted experimental investigations that demonstrated the potential for enhancing the mechanical properties of SCC at both 28 d and 180 d by incorporating steel fibers and replacing up to 30% of the cement with FA. However, they also observed a decline in both compressive and flexural strength with an increase in FA content within the SCC mixture. Subsequent studies by Liu et al. [12] and Sahar et al. [13] focused on the effects and underlying mechanisms of high dosages of FA on the durability of SCC. Their findings suggest that an optimal replacement ratio of FA can significantly enhance the corrosion resistance of SCC. Jabbar et al. [14] and Velichko et al. [15] further examined the impact of partially replacing cement with FA in SCC, noting improvements in workability and strength. Kristiawan et al. [16] delved into the porosity of SCC containing a high dosage of FA, revealing that the age of the concrete is a critical factor affecting the influence of FA content on porosity. Their research indicated that FA tends to increase porosity when the concrete is less than 56 days old, whereas it has a reducing effect on porosity at an age of 90 d.

In conclusion, fly ash, as an active additive, has received increasing attention and recognition for its role in further developing high-performance concrete. It not only improves various properties of concrete but also brings about higher economic and social benefits.

Steel fibers are fiber materials made from steel and are typically characterized by high strength and toughness. When these fibers are uniformly dispersed throughout the concrete in a multidirectional manner, they act as a reinforcement mechanism that significantly impedes the propagation of micro-cracks and mitigates the likelihood of macro-crack formation. This enhancement in the fracture toughness of the concrete is attributed to the interaction between the steel fibers and the surrounding cementitious matrix, which facilitates energy dissipation and redistributes stress concentrations that would otherwise lead to crack propagation. Therefore, the addition of steel fibers to concrete is a way to improve the overall durability and structural reliability of the material, especially in applications where crack resistance is critical.

A series of investigations have sought to elucidate the impact of steel fiber geometry on the properties of steel fiber-reinforced self-compacting concrete (SFRSCC), both in its fresh and hardened states. Sulthan et al. [17,18] reported that an escalation in the volume fraction of steel fibers is correlated with a decrease in the workability of SFRSCC, highlighting the need for a balance between reinforcement and workability in mix design. Zhuang et al. [19] and Sivanantham et al. [20] delved into the influence of the fiber aspect ratio on the fresh properties and strength characteristics of SFRSCC. Their research has demonstrated that while the addition of fibers exerts a moderate influence on the compressive strength of self-compacting concrete, there is a pronounced enhancement observed in both flexural and tensile strengths. The aspect ratio of the fibers is found to have a minimal effect on compressive strength; however, it has been shown to have the potential to moderately increase the tensile strength of SCC when optimized. Siddique et al. [21] examined the effects of steel fibers on the rheological behavior, as well as the strength and permeability properties, of SCC. Their findings indicate that an increase in fiber content leads to an overall improvement in concrete performance, with notable enhancements in compressive, splitting tensile, and flexural strengths. Gong et al. [22] explored the impact of varying volume fractions and combinations of steel fibers on the tensile properties of high-strength SFRSCC (HSFRSCC). The results of their investigation suggest that the incorporation of hybrid steel fibers can significantly bolster the tensile performance of the concrete, offering a promising avenue for improving the structural integrity and durability of SCC in applications where tensile resistance is critical. Fayed et al. [23,24] conducted an experimental study on the bearing strength of recycled aggregate concrete reinforced with steel fibers (volume fractions are 0.5%, 1.5% and 2%) and the performance of steel fibers with 1%, 2% and 3% reinforced-concrete columns. Kalkan et al. [25] studied the shear capacity of CNC scrap steel fibers and showed that the advantages of using scrap lathe waste emerge from several perspectives, including the type and quantity of the steel fibers and the range of reinforcement.

Based on the aforementioned studies, it is evident that both domestic and international researchers place significant importance on the addition of steel fibers to concrete. Various types of steel fibers added to concrete have a series of effects on its mechanical and workability properties. Suitable levels of admixture and volume fractions of steel fibers can effectively improve the high strength and durability of concrete [26,27].

Traditional steel fiber-reinforced concrete typically uses steel fibers with larger diameters, usually around 0.5 mm, and longer lengths, typically around 30 mm. The longer length of steel fibers can result in poor workability of the concrete mixture. Additionally, when the fiber content is high, the strength of the concrete may decrease due to the uneven distribution of fibers.

Chen et al. [28] conducted experimental research on the effects of micro-steel-wire steel fibers on the workability and fundamental mechanical properties of self-compacting concrete (SCC). Their findings indicate that, by meticulously adjusting the dosage of cementitious materials, high-efficiency water-reducing agents, and aggregates, it is feasible to increase the volume fraction of micro-steel-wire steel fibers to 3% or higher without compromising workability. Concurrently, the strength of SCC incorporating these fibers escalates with the increments of the fiber volume fraction. However, the study did not explore the impact of varying admixtures and the use of shorter steel fibers on the performance of SCC. Alomayri et al. [29], in their research, investigated the mechanical properties of micro-steel-wire steel fiber–fly ash geopolymer composites, with a particular focus on the influence of varying amounts of nano-silica. The micro-steel fibers utilized in their study had dimensions of 11 mm in length and 0.2 mm in diameter. Ye et al. [30] prepared specimens of micro-fine steel fiber–high-strength lightweight aggregate concrete (MSFHLAC) using micro-fine steel fibers of 13 mm in length and 0.2 mm in diameter, high-strength shale aggregate, and mineral admixtures. They assessed the influence of micro-fine steel fiber volume fraction, sand ratio, and the water–cement ratio on the static mechanical properties, including compressive strength, splitting tensile strength, flexural strength, shear strength, and the flexural toughness of MSFHLAC specimens. Ma [31] and Feng [32] independently examined the influence of micro-steel fibers on the properties of concrete. Their results collectively demonstrate that the incorporation of micro-steel fibers can significantly enhance the strength of concrete. Furthermore, they highlight that fibers with different aspect ratios and volume fractions exert a substantial impact on the strength of concrete when compared to conventional steel fibers. While these studies have considered the use of ultra-fine steel fibers and diverse admixtures, the specific contribution of shorter steel fibers to the improvement of SCC has not been the primary focus of investigation. In separate analyses, Yuan et al. [33] and Öz et al. [34] evaluated the effects of fly ash on the properties of steel fiber concrete. Yuan et al. investigated the role of fly ash in enhancing the frost resistance of steel fiber concrete, while Öz et al. focused on its impact on the mechanical properties of the material. Both studies contribute to the broader understanding of how supplementary materials can be integrated into steel fiber concrete to achieve improved performance characteristics.

Research is lacking on how extra-short extra-fine steel fibers improve the mechanical and workability of concrete. There is a need for further studies, particularly on their use in self-compacting concrete with fly ash. The existing literature mainly examines traditional steel fiber-reinforced concrete and the effects of admixtures on SCC, with little exploration of the combined use of these fibers with SCC and admixtures.

This study advances a novel methodology within the fields of self-compacting concrete and steel fiber-reinforced concrete. It involves the substitution of 30% of the total binder content with Class I fly ash and the introduction of extra-short extra-fine steel fibers as an alternative to the conventional larger-diameter and longer steel fibers. The volume fraction of steel fibers is meticulously varied across levels of 0%, 1.5%, 3%, 5%, and 6% within the concrete mixture. The determination of the most effective mix proportions is achieved through a series of experimental optimizations. The primary focus of the experimental investigation is to assess the effects of steel fiber content on the compressive strength, axial compressive strength, splitting tensile strength, and flexural strength of SCC. Additionally, a comparative analysis with ordinary concrete is conducted to delineate the performance benefits of the enhanced SCC.

2. Experimental Materials and Mixture Proportion

2.1. Raw Materials

2.1.1. Cement

In this experiment, 42.5-grade ordinary Portland cement (Hongshi brand) produced in the neighboring county of Sichuan province was used, and its chemical composition and physical mechanics indexes are shown in Tables 1 and 2.

Table 1. 42.5-grade ordinary silicate cement chemical composition (%).

Components	SiO_2	Fe_2O_3	CaO	Al_2O_3	MgO	SO_3	Loss
Content	22.7	3.24	61.3	6.92	2.15	2.46	3.13

Table 2. Physical and mechanical properties of 42.5-grade ordinary Portland cement.

Density (g/cm^2)	Specific Surface (m^2/kg)	Volume Stability	Standard Consistency Water Consumption (%)	Setting Time (min)		Compressive Strength (MPa)		Rupture Strength (MPa)	
3.08	346	conformity	26.6	initial set	final set	3 d	28 d	3 d	28 d
				205	278	22.6	48.9	4.8	8.6

2.1.2. Fly Ash

The fly ash used in this paper is Class I fly ash produced by Henan Zhengzhou Hengyuan New Material Co., Ltd., which is located in Zhengzhou, China, with a moisture content of $0.85\% \leq 1.0\%$, density of 2.55 g/cm^3, and specific surface area of 4800 cm^2/g, according to the standard GB/T1596-2005 [35], the components of which are tested in Table 3. The Class I fly ash used in this paper is shown in Figure 1.

Table 3. Class I fly ash composition content index (%).

Composition	Loss	Al_2O_3	SiO_2	SO_3	CaO	Cl-	Alkali Content	Iron Content
Content	2.8	24.2	45.1	2.1	5.6	0.015	1.2	0.85

Figure 1. Class I fly ash.

2.1.3. Coarse Aggregate

In light of the stringent performance requirements for self-compacting concrete (SCC), coupled with the intricacies of reinforcement placement and the challenges posed by suboptimal pouring conditions, the utilization of coarse aggregates with excessively large particle sizes is deemed inadvisable. Such aggregates have the potential to compromise the flowability of the SCC mixture and may precipitate issues such as segregation and layering phenomena. To mitigate these risks, this study employs limestone crushed stones as coarse aggregates within the ranges of 5 mm to 10 mm and 10 mm to 15 mm. These aggregates are combined in an equal proportion, that is, a 1:1 ratio, to ensure an optimal balance of properties within the SCC mixture. The physical and mechanical properties of the utilized crushed stones are detailed in Table 4.

Table 4. Coarse aggregate performance index.

Apparent Density (kg/m^3)	Packing Density (kg/m^3)	Voidage (%)	Soil Content (%)	Needle-Flake Granules (%)
2758	1560	40.8	0.35	5.6

2.1.4. Fine Aggregate

In the formulation of self-compacting concrete (SCC), a significant proportion of sand is commonly incorporated. However, the selection of sand with an excessively fine gradation can exert a detrimental influence on the mechanical properties of SCC. Notably, the use of fine sand, characterized by a larger specific surface area, can escalate the water demand, thereby negatively impacting the flowability of the mixture. To address these concerns, this study has elected to utilize medium sand for the SCC mix design. The physical properties of the sand are presented in Table 5.

Table 5. Physical performance index of sand.

Apparent Density (g/cm^3)	Bulk Density (g/cm^3)	Fineness Modulus	Soil Content (%)
2.48	1.39	2.64	0.85

2.1.5. Water

Ordinary tap water was used as mixing water.

2.1.6. Steel Fiber

The steel fibers used in this experiment are extra-short extra-fine steel fibers with a copper coating, produced by Shandong Liaocheng Hongshengyuan Metal Products Co., Ltd, which is located in Liaocheng, China. Due to their extra-short extra-fine characteristics, these steel fibers can be used in high dosages in self-compacting concrete. Meanwhile, the copper coating of steel fibers is a performance-enhancing technique for concrete in which a layer of copper is electroplated onto the surface of steel fibers. This treatment can augment corrosion resistance, improve bond strength with the concrete, and enhance electrical conductivity and thermal stability, thereby potentially elevating the durability, crack resistance, and fire resistance of concrete. The specific mechanical properties of the steel fibers are listed in Table 6.

Table 6. Physical performance index of steel fiber.

Fiber Type	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength (MPa)
Copper-plated steel fiber	6 ± 1	0.18–0.22	30	2869

The extra-short extra-fine steel fibers used in this study have a length of only 6 mm and a diameter of 0.2 mm (as shown in Figure 2). The addition of these fibers in concrete can greatly enhance its properties, with a maximum dosage of 6% to 7%. Furthermore, even after adjusting the mix proportions appropriately, the self-compacting effect can still be achieved.

(**a**)

(**b**)

Figure 2. Extra-short extra-fine steel fibers: (**a**) length; and (**b**) diameter.

2.1.7. High-Range Water-Reducing Admixture

The water-reducing admixture used in this experiment is a standard polycarboxylic acid high-performance water-reducing admixture produced by Chongqing Sansheng Industrial Co., Ltd, which is located in Chongqing, China. Its solid content is 17.76%, the water-reducing rate is 30%, and the recommended dosage is 1.2% to 2.0%.

2.2. Mixture Proportion

The self-compacting concrete (SCC) developed in this study, reinforced with extra-short extra-fine steel fibers, is designated with a strength grade of C40. In accordance with the specifications, the formulated SCC must adhere to the performance criteria outlined in Table 7.

Table 7. Design requirements for self-compacting concrete work performance.

Self-Compacting Performance	Performance Index	Performance Grade	Technical Requirement
Fillability	Slump flow (mm)	SF	550~850
	Time (s)	VS	2~20
Gap passability	Difference between slump flow and J-ring extensibility (mm)	PA	0~50
Resistance to separation	Segregation rate (%)	SR	≤20

According to the design of the dosage of admixture and the dosage of steel fibers, the mix proportion of extra-short extra-fine steel fiber self-compacting concrete was designed, tested, and adjusted. The mix proportion of steel fiber self-compacting concrete with a single addition of 30% fly ash is shown in Table 8.

Table 8. The mix design of self-compacting concrete with 30% fly ash and steel fibers added.

Number	Cement (kg)	Water (kg)	Fly Ash (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Water-Reducing Admixture (kg)	Steel Fiber
A0	446	185	191	750	750	5.2	0%
A1	446	185	191	750	750	5.2	1.5%
A2	493	205	211	700	700	5.6	3%
A3	550	220	235	650	650	6	5%
A4	612	240	272	600	600	8	6%

The notation Ai (where i is 0, 1, 2, 3, 4) represents the dosage of steel fibers, with percentages of 0%, 1.5%, 3%, 5%, and 6% respectively.

3. Test Methods

3.1. Working Performance Experiment

3.1.1. Slump Flow Test

The slump test, a standard procedure for assessing the workability of a concrete mixture, is conducted as follows. Initially, the slump cone and base plate are moistened to prevent adhesion of the concrete, ensuring that there is no standing water on the surface of the equipment. The slump plate is then positioned on a level surface, with the slump cone placed centrally upon it. During the filling of the cone with the concrete mixture, both sides of the cone are firmly stepped on to prevent the mixture from flowing out from the bottom during the filling process. The mixture, which must be well-mixed and free of segregation, is added swiftly and continuously. Post-filling, any excess mortar is leveled off using a trowel, and surplus mixture around the cone is removed. The cone is subsequently lifted vertically in a steady motion over approximately 300 mm within 3 s, with the entire process from filling to lifting completed within 1.5 min. The slump spread is observed until it stabilizes, after which measurements are taken using a ruler to record the maximum diameter and its perpendicular counterpart. The slump value is calculated as the average of these two diameters in millimeters, with the measurement process concluded within 40 s after lifting the cone. The slump test process is outlined in Figure 3.

Figure 3. Slump flow test: (**a**) experimental procedure; and (**b**) experimental results.

3.1.2. V-Funnel Test

The V-funnel test, as illustrated in Figure 4, is a test method to check the segregation resistance of self-compacting concrete. The test begins with the V-funnel being positioned vertically on a horizontal and smooth surface, ensuring proper alignment. The inner walls of the funnel are pre-wetted with water and any excess water is removed to maintain the moisture level. A receiving container is then placed at the funnel's outlet, located at the base, and the outlet is temporarily closed before the commencement of the test. The concrete is poured into the funnel from the top in a uniform and rapid motion, ensuring that the flow is not impeded. Any excess mixture on the funnel's exterior is promptly removed. Following a one-minute settling period, the bottom valve is opened, initiating the flow of the concrete into the container. A stopwatch is used to precisely record the flow time from the start of the opening of the valve to the complete flow of the mixture, with accuracy to the nearest 0.1 s. Throughout the experiment, careful observation is maintained to identify any blockages or irregularities in the flow of the concrete.

Figure 4. V-funnel test.

3.1.3. L-Box Test

The L-box test, as outlined in Figure 5, is a used to evaluate the passing ability of a self-compacting concrete. The procedure initiates with positioning the L-shaped mold on a level and solid surface and ensuring that the movable partition at the junction of the vertical and horizontal sections is securely closed. The interior surfaces of the mold are pre-wetted to create a moist environment, and any standing water is promptly removed to avoid altering the concrete's water content. A well-mixed concrete sample is then poured into the vertical section of the L-box, filling it to the brim. The top surface of the concrete is leveled using a shovel. Following this, the concrete is given a one-minute settling period to allow for any large air bubbles to escape and for the material to slightly consolidate. Upon lifting the partition, the flow of the concrete from the vertical to the horizontal section is initiated, and a timer is started concurrently. The timer is halted when the leading edge of the concrete flow reaches the bottom of the horizontal section. Throughout the flow, the time taken for the concrete to reach the 200 mm and 400 mm marks on the horizontal section is meticulously recorded. Once the flow ceases, the height difference between the front and back ends of the concrete within the horizontal section is measured. This measurement indicates whether the concrete has self-leveled. It is imperative that the entire L-box test, from pouring to measurement, is conducted within a strict timeframe of 5 min to ensure the validity of the results.

Figure 5. L-box test.

3.2. Mechanical Properties Test

To determine the effects of extra-short extra-fine steel fibers on the mechanical properties of single-mixed fly ash self-compacting concrete, a cubic compression test, axial compression test, split tensile test and flexural strength test were designed, and the tests were all designed according to GB/T50081-2019 [36].

3.2.1. Cube Compressive Test

In order to evaluate the cubic compressive properties, two groups of cubic compressive strength specimens were fabricated with five different volume dosages of steel fibers at 7 d and 28 d. Each group of specimens had a size of 100 mm × 100 mm × 100 mm, and there were 30 specimens in total. Immediately after casting, the surface of the specimens was covered with waterproof cling film and left at about 20 °C for about one day until demolding. Immediately after demolding, the specimens were placed in a standard curing chamber also maintained at about 20 °C. During placement, care is taken to leave sufficient space between each specimen and to water the specimens periodically to cure, avoiding direct contact with high-pressure water streams to prevent damage to the specimens. After reaching the appropriate age, the specimens were removed from the curing chamber and their dimensions were recorded. The loading test was carried out on a 3000 KN universal testing machine with a loading rate of 0.5 MPa/s. The specimens and test procedure are shown in Figure 6.


(**a**) (**b**)

Figure 6. Cube compressive strength test: (**a**) cubic compressive specimen; and (**b**) compression test procedure.

3.2.2. Axial Compressive Test

The dimensions of the specimens for this test section were 100 mm × 100 mm × 300 mm. A total of 30 prismatic specimens were tested for their axial compressive strength at both 7 d and 28 d of age. The testing procedure followed the operating guidelines of the universal testing machine, where the prisms, after being cured to the appropriate age, were vertically placed on the testing machine. The concrete specimens were adjusted to center the prism between the upper and lower plates. Then, the pressure plate was manually adjusted to make contact with the specimen, and finally, the loading test was conducted at a rate of 0.5 MPa/s until the specimen failed. Figure 7 shows the axial compressive specimens and the testing setup.

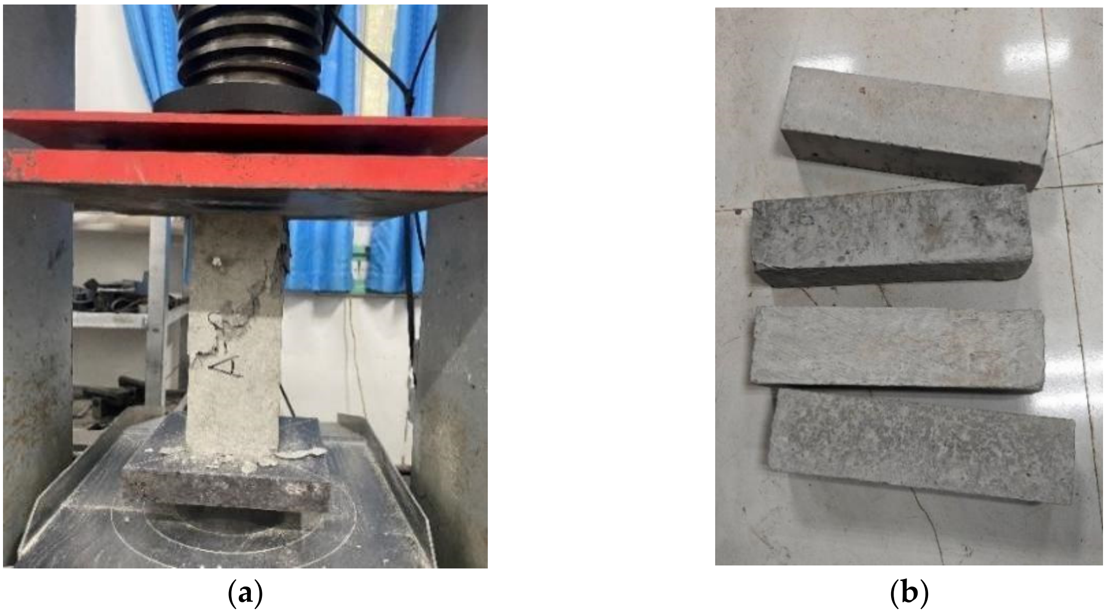

(**a**) (**b**)

Figure 7. Axial compressive strength test: (**a**) axial compressive test procedure; and (**b**) axial compressive specimen.

3.2.3. Splitting Tensile Strength Test

Cubic specimens of 100 mm × 100 mm × 100 mm were used in this test to study the splitting compressive strength of concrete. Before starting the test, the upper plate of the press is adjusted to a suitable position. First, the steel bedding is put on the bottom, the flat side is directly in contact with the lower bearing surface of the press, and the steel bedding is put in the center position. Then, the wooden bedding is put on, and the test block to be tested is put on the bedding immediately afterwards. The steel bedding should be in the middle of the test block and the wooden bedding. The upper layer of the test block is operated in the same way. Then, the lifting button of the universal machine is manually controlled until the upper plate of the press is fitted with the matting layer, and the test block as a whole is kept stable Finally, the test device is started to measure the split tensile strength. The test process is shown in Figure 8.

Figure 8. Splitting tensile test.

3.2.4. Bending Test

The experimental specimens were 100 mm × 100 mm × 400 mm cubic trabecular specimens. First, the flexural strength test was carried out on 30 small beam specimens with 5 groups of ratios from 0 to 6% with steel-fiber doping in the case of the single-doped fly ash. The loading rate of the testing machine was 0.05 MPa/s, and the test was conducted until the specimens were damaged in order to record the data.

4. Results and Discussion

4.1. Fresh State Properties

The change rules for each work performance index with the steel fiber mixing amount of extra-short extra-fine steel fiber self-compacting concrete with a single mixing of fly ash was plotted according to Table 9, and are shown in Figures 9–12, respectively.

Table 9. Work performance results.

Specimen	Slump Flow (mm)	V-Funnel (s)	L-Box (s)	L-Box Horizontal Height Difference (mm)
A0	705	24	9	5
A1	695	40	17	15
A2	680	125	32	43
A3	640	169	49	78
A4	615	193	64	74

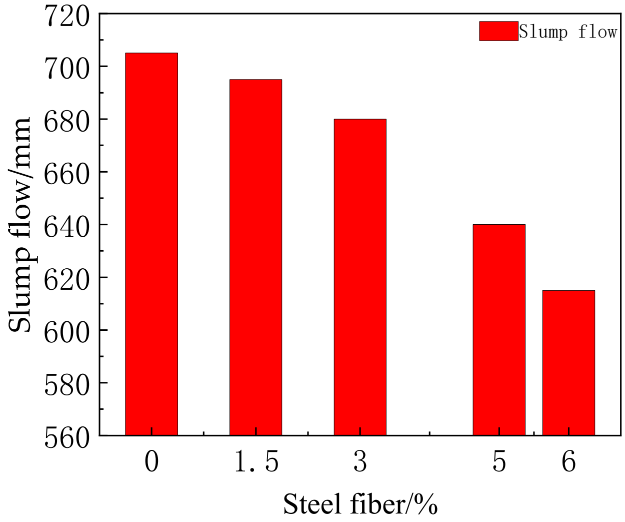


Figure 9. Effect of steel fiber percentages on slump flow test.

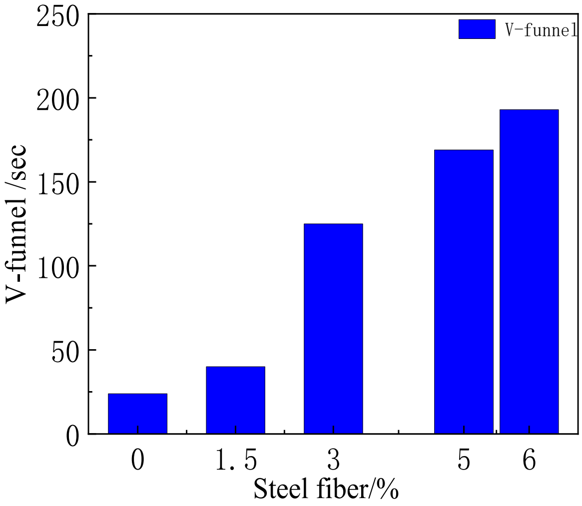


Figure 10. Effect of steel fiber percentages on flow time at V-funnel test.

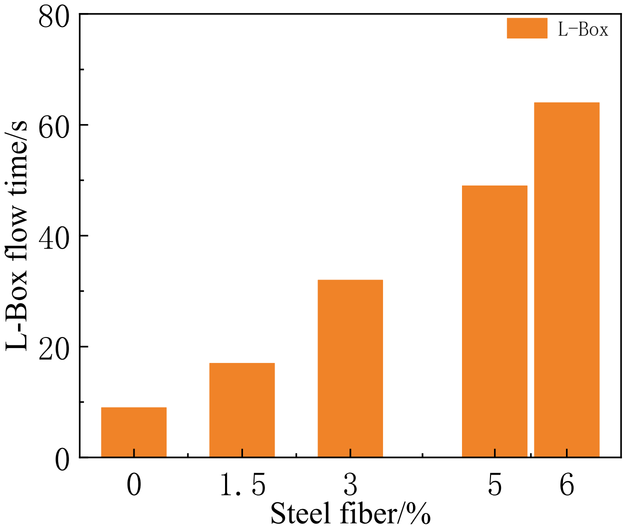


Figure 11. Effect of steel fiber percentages on L-box test.

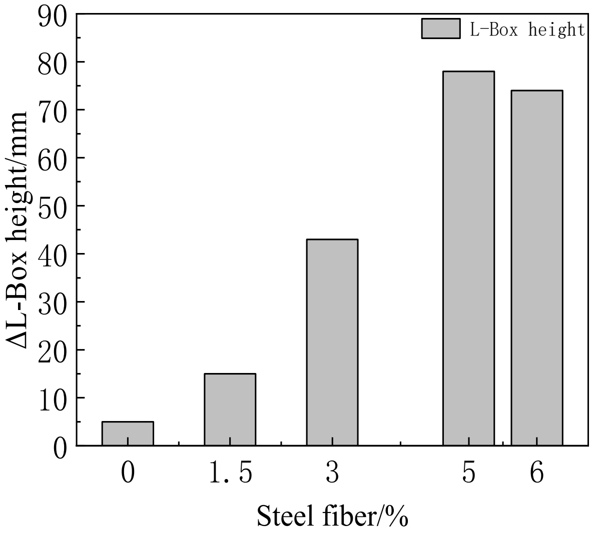


Figure 12. Height difference between front and rear of L-box.

4.1.1. Slump Flow Test (Filling Ability)

The slump flow test is a method used to evaluate the fluidity and stability of concrete mixtures, with a larger slump flow indicating better fluidity. The results of the slump flow test indicated that as the fiber content increased, the slump flow gradually decreased.

Figure 9 illustrates the impact of steel fiber content on the slump flow of self-compacting concrete (SCC). In the absence of steel fibers, the maximum slump flow measured is 705 mm. The introduction of 1.5% steel fibers into the mixture have a negligible effect on the slump flow, which remain high at 695 mm. Even at a steel fiber content of 3%, the slump flow value is relatively stable at 680 mm. However, a more substantial decline in slump flow is observed as the steel fiber content is further increased to 5% and 6%. Under these conditions, the slump flow diminished to a minimum of 615 mm, representing a significant decrease of 12.7% relative to that without fibers. This reduction can be attributed to the increasing void ratio within the concrete mixture, a consequence of the additional volume occupied by the fibers, particularly when using extra-short extra-fine steel fibers. Furthermore, an excessive amount of steel fibers may become entrapped within the aggregate and mortar matrix, which can disrupt the flowability of the concrete. The interplay between fiber content and the material's inherent characteristics thus has a discernible impact on the workability of the SCC, with the potential to compromise its self-compacting properties if the fiber concentration is not appropriately calibrated. According to JGJ/T283-2012 [37], the minimum requirement of the slump extension is 550 mm, and the test results meet the requirements.

While the addition of steel fibers to self-compacting concrete enhances its crack resistance and toughness, it can also result in diminished slump, impacting the construction process. The decreased fluidity can elevate the complexity of pumping operations, potentially reducing construction efficiency, and increasing costs. Furthermore, the uniformity and compactness of the concrete may be compromised, which could subsequently impact its durability and ultimate strength.

4.1.2. V-Funnel Test (Cohesiveness)

The V-funnel test measures the time it takes for concrete to flow through a funnel of a specific shape to assess its fluidity and resistance to segregation, with shorter times indicating better fluidity. The results of the V-funnel test show that the higher the fiber content, the longer it takes for the fly ash-only mixture to flow through the V-type apparatus.

Figure 10 delineates the influence of extra-short extra-fine steel fiber content on the flow time of a fly ash-incorporated self-compacting concrete (SCC) mixture through a V-type apparatus. When the steel fiber content is maintained below or at 3%, the flow times for the mixture are notably brief, recorded at 24 s and 40 s, respectively. However, upon surpassing a 3% steel fiber content, there is a pronounced escalation in flow time, ranging from 120 s to 193 s with incremental fiber additions. Despite the extended flow times, all the mixtures still conform to the stringent requirements set forth for SCC. Although the addition of high volumes of steel fibers negatively affects the fluidity of the mixture, it simultaneously significantly enhances its viscosity. The extra-short extra-fine steel fibers are tightly enveloped within the paste and aggregates, providing a scientific basis for the improvement in the mechanical performance and toughness of the hardened mixture. The incorporation of higher volumes of steel fibers, while somewhat detrimental to the fluidity of the mixture, introduces a significant enhancement in its viscosity. This increase in viscosity is attributed to the fibers being closely enveloped within the cement paste and aggregate framework, thereby augmenting the mixture's resistance to deformation. This encapsulation effect not only preserves the self-compacting nature of the concrete but also imparts a substantial improvement in the mechanical performance and toughness of the hardened matrix. Consequently, the judicious balance of steel fiber content provides a scientific rationale for optimizing the trade-off between fluidity and toughness in the design of SCC mixtures.

4.1.3. L-Box Test (Passing Ability)

The L-box test simulates the ability of concrete to flow through obstacles, such as reinforcement bars during actual construction, thereby assessing the workability of the concrete. Figures 11 and 12 show the results of the L-box test, indicating that as the fiber content increases, the passage time of the mixture through the L-box gradually increases, and the height difference between the front and back ends of the horizontal box after the mixture stops flowing becomes larger.

The L-box test results, as detailed in Figure 10, provide insights into the passage time and height differences of self-compacting concrete (SCC) with varying steel fiber contents. When the steel fiber content is below or equal to 3%, the passage time is significantly faster, with measurements of 9 s and 17 s, respectively. This rapid flow to the bottom of the box underscores the excellent flowability of the mixture at these fiber levels. Conversely, at a steel fiber content of 6%, the passage time is observed to be maximized at 64 s, indicating a substantial reduction in flowability with increased fiber content. In terms of height difference, the mixture with 0% steel fiber content exhibits a rapid flow capability, resulting in a minimal height difference of 5 mm. As the steel fiber content increases to 3%, the height difference reaches 43 mm, and further rises to a maximum of 78 mm at 5% fiber content. The height difference is a critical parameter in assessing the penetrating performance of the mixture; a larger height difference correlates with diminished penetrating ability. This reduction in performance is attributed to the increased presence of steel fibers, which occupy the interstitial spaces between the aggregates and the matrix. The fibers, by coating the aggregate surfaces, impede their relative displacement and prevent the mortar from fully encapsulating the aggregates. This interaction results in a loss of fluidity, hindering the mixture's ability to rapidly traverse through the rebar mesh and reducing its overall penetration.

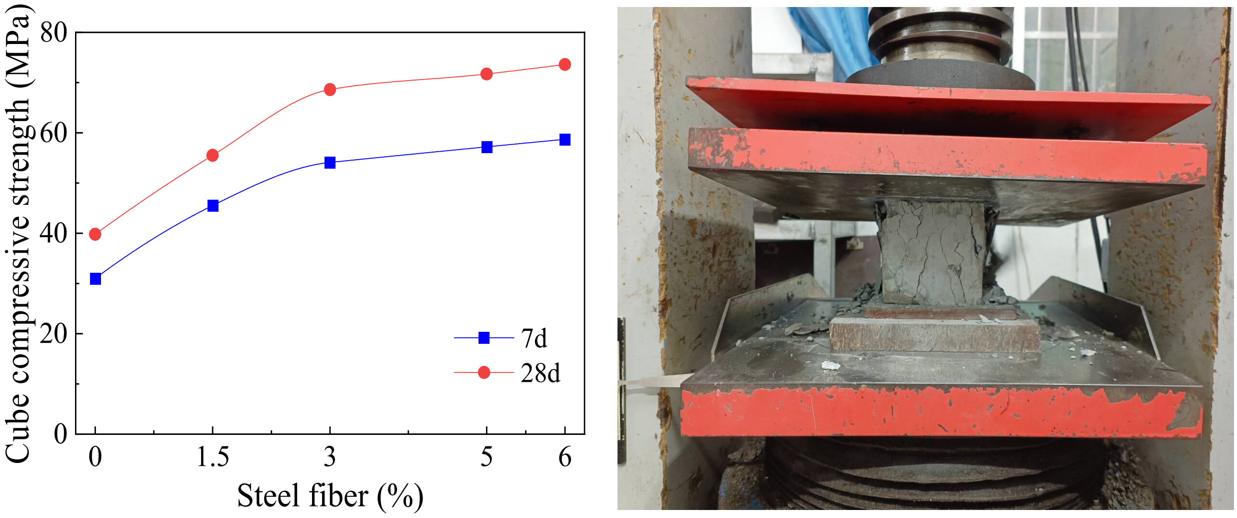
4.2. Mechanical Properties

4.2.1. Cube Compressive Strength

Combined with Table 10 and Figure 13, it can be seen that with the gradual increase in fiber admixture, the cubic compressive strength of concrete at 7 d and 28 d are increased, and the maximum reaches 58.7 MPa at 7 d and 73.6 MPa at 28 d.

Table 10. Cube compressive strength test results.

Number	Steel Fiber (%)	Cube Compressive Strength (MPa)	
		7 d	**28 d**
A0	0	31.0	39.8
A1	1.5	45.5	55.5
A2	3	54.1	68.6
A3	5	57.2	71.7
A4	6	58.7	73.6



(**a**) (**b**)

Figure 13. Cube compressive strength test results: (**a**) compressive strength; and (**b**) destructive form.

When the steel fiber dosage increases from 0% to 3%, the cubic compressive strength of the concrete is improved by a large margin. At 7 d, the dosage of 3% of the compressive strength has been increased by 74.5%, at 28 d it has been increased by 72.3%. This is because when the water in the concrete gradually disappears, the steel fibers are tightly adhered to the aggregate and mortar, increasing the friction between the aggregates and the internal structure of the concrete to produce a certain binding force. The internal structure of the concrete has a certain binding force, and the chaotic distribution of steel fibers further increases the cubic compressive strength of concrete. However, the increased speed in compressive strength begins to slow when the steel fiber content reaches 3%, as the amount of steel fibers becomes relatively high and approaches a saturation point. The excessive addition of steel fibers may lead to unstable variations in the compressive strength of the concrete cubes.

Upon examination of Figure 13b, it is evident that the specimen with steel fibers initiates a small, central crack upon reaching its maximum load-bearing capacity. This crack formation is attributed to the dense network of steel fibers within the concrete, which are not only present in high volume but also uniformly dispersed. Consequently, rather than experiencing abrupt failure, the specimen maintains its structural integrity and continues to sustain the applied force. Subsequently, the crack propagates from the four edges, demonstrating a characteristic ductile behavior indicative of the fibers' ability to enhance the material's toughness and ductility.

4.2.2. Axial Compressive Strength

As presented in Table 11 and illustrated in Figure 14, the axial compressive strength of the concrete mixture attains its highest values at 44.5 MPa and 54.8 MPa at the ages of 7 d and 28 d, respectively. At the age of 7 d, the axial compressive strength experiences a substantial increase from 21.7 MPa to 43.2 MPa with a maximum enhancement of 99.1% as the dosage of steel fibers escalates from 0% to 6%. By 28 d, the rate of increase in axial compressive strength, while slightly less pronounced than at 7 d, still demonstrates a significant rise from 29.4 MPa to 54.8 MPa, corresponding to a maximum increase of 86.5%.

Table 11. Axial compressive strength test results.

Number	Steel Fiber (%)	Axial Compressive Strength (MPa)	
		7 d	28 d
A0	0	21.7	29.4
A1	1.5	33.4	41.6
A2	3	40.1	50.7
A3	5	44.5	53.8
A4	6	43.2	54.8

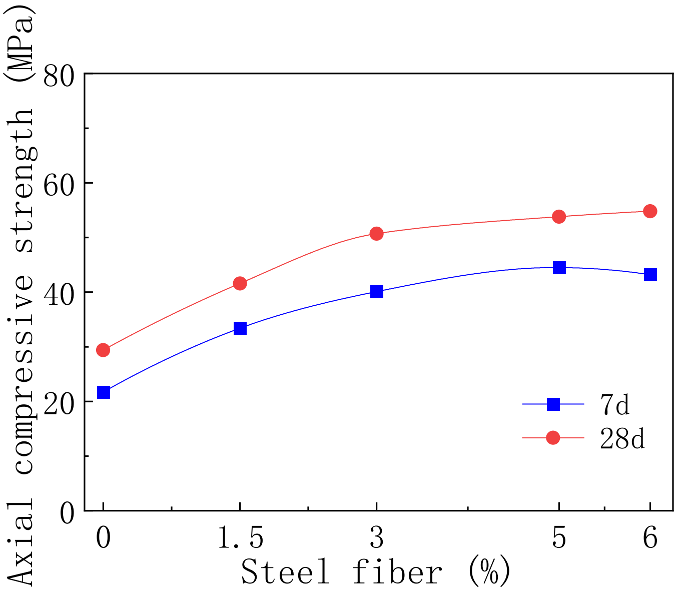


Figure 14. Axial compressive strength test results.

The most rapid escalation in axial compressive strength is detected within the initial increment of steel fiber content from 0% to 3%. This surge can be attributed to the sufficient voids present within the aggregate and mortar, which, upon the introduction of steel fibers, become effectively filled, thereby substantially bolstering the compressive strength. Concurrently, the early stage of the cement hydration reaction proceeds swiftly, further accelerating the gain in strength. However, as the steel fiber content progresses from 3% to 6%, the rate of growth in axial compressive strength diminishes. This deceleration occurs as the steel fiber dosage approaches the optimal limit for self-compacting properties, beyond which the fibers' ability to enhance strength reaches a plateau.

4.2.3. Splitting Tensile Strength

The results of the splitting tensile strength test, obtained after testing 30 cubic tensile test blocks, are shown in Table 12 and plotted in Figure 15.

Table 12 and Figure 15 present the findings pertaining to the splitting tensile strengths. The results demonstrate a positive correlation between the splitting tensile strength and both the steel fiber content and the curing age of the concrete. Specifically, the splitting tensile strength escalates to 7.1 MPa at 7 d and reaches 9.8 MPa at 28 days. At the 7-day mark, an increment in steel fiber content from 0% to 6% results in a substantial increase in splitting tensile strength, from 3.2 MPa to 7.1 MPa—a notable enhancement of 121.9%.

By 28 days, the strength continues to rise with increasing steel fiber content, from 5.4 MPa to 9.8 MPa, representing the highest increase of 81.5%. These observations confirm the significant contribution of steel fibers to the enhancement of SCC's splitting tensile strength.

Table 12. Splitting tensile strength test results.

Number	**Steel Fiber (%)**	**Splitting Tensile Strength (MPa)**	
		7 d	**28 d**
A0	0	3.2	5.4
A1	1.5	4.1	6.5
A2	3	5.3	8.2
A3	5	6.7	9.6
A4	6	7.1	9.8

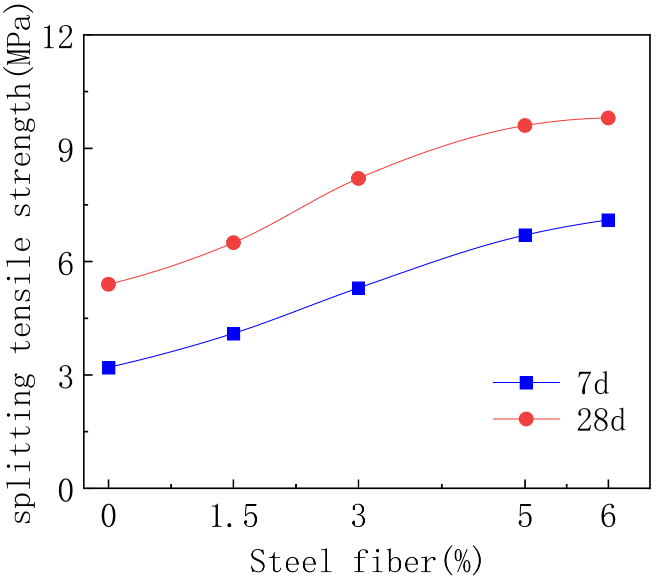


Figure 15. Splitting tensile strength test results.

Due to the special properties of the fiber material, the presence of steel fibers effectively suppresses instability within the concrete during the hardening process, preventing the formation of cracks. Even if fine cracks do form, they can be well contained to prevent propagating, which demonstrates the crack-arresting effect of steel fibers and explains, from another perspective, the enhancement of the concrete's tensile strength due to the addition of steel fibers.

4.2.4. Flexural Strength

The experimental data presented in Table 13 and depicted in Figure 16 reveal that the optimum flexural strength is attained with a steel fiber content of 5%, which corresponds to values of 7.4 MPa at 7 d and 12.8 MPa at 28 d. The most significant enhancements in flexural strength are observed when the steel fiber content is incremented from 3% to 5%, resulting in improvements of 61.2% and 75.5% at 7 d and 28 d, respectively. The failure mode of the specimen's post-fiber incorporation exhibits increased ductility, characterized by a fracture surface that remains interconnected by the steel fibers, preventing complete disintegration. These findings suggest that the inclusion of steel fibers significantly ameliorates the flexural performance of self-compacting concrete (SCC) and reduces its brittleness. However, a notable decline in flexural strength is observed when the steel fiber content surpasses 5%. This decrement is hypothesized to stem from an overabundance of fibers within the concrete, which may lead to a detrimental impact on the workability and, consequently, the composite action of the fibers and the cementitious mix.

Table 13. Flexural strength test results.

Number	Steel Fiber (%)	Flexural Strength (MPa)	
		7 d	28 d
A0	0	3.6	4.9
A1	1.5	4.3	7.7
A2	3	5.2	9.1
A3	5	7.4	12.8
A4	6	6.8	11.5

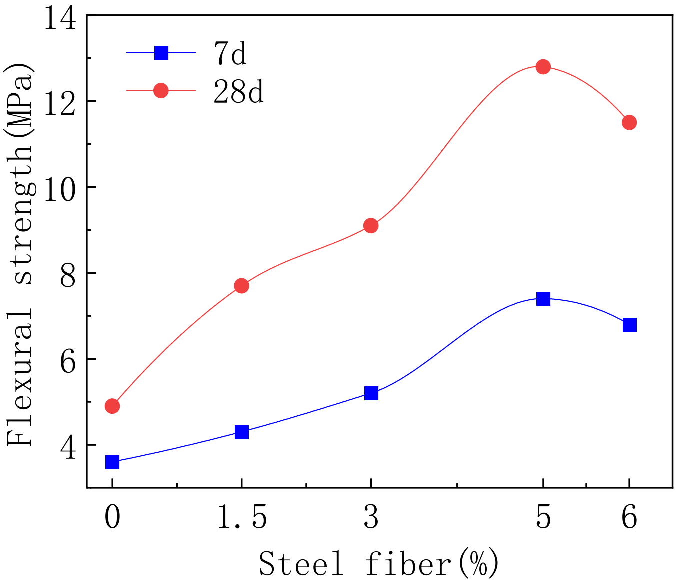


Figure 16. Flexural strength test results.

The relationship between the compressive strength and flexural strength of concrete was analyzed and the results of the compression to flexural strength ratio were obtained, as shown in Table 14.

Table 14. The relationship between flexural strength and cubic compressive strength of concrete.

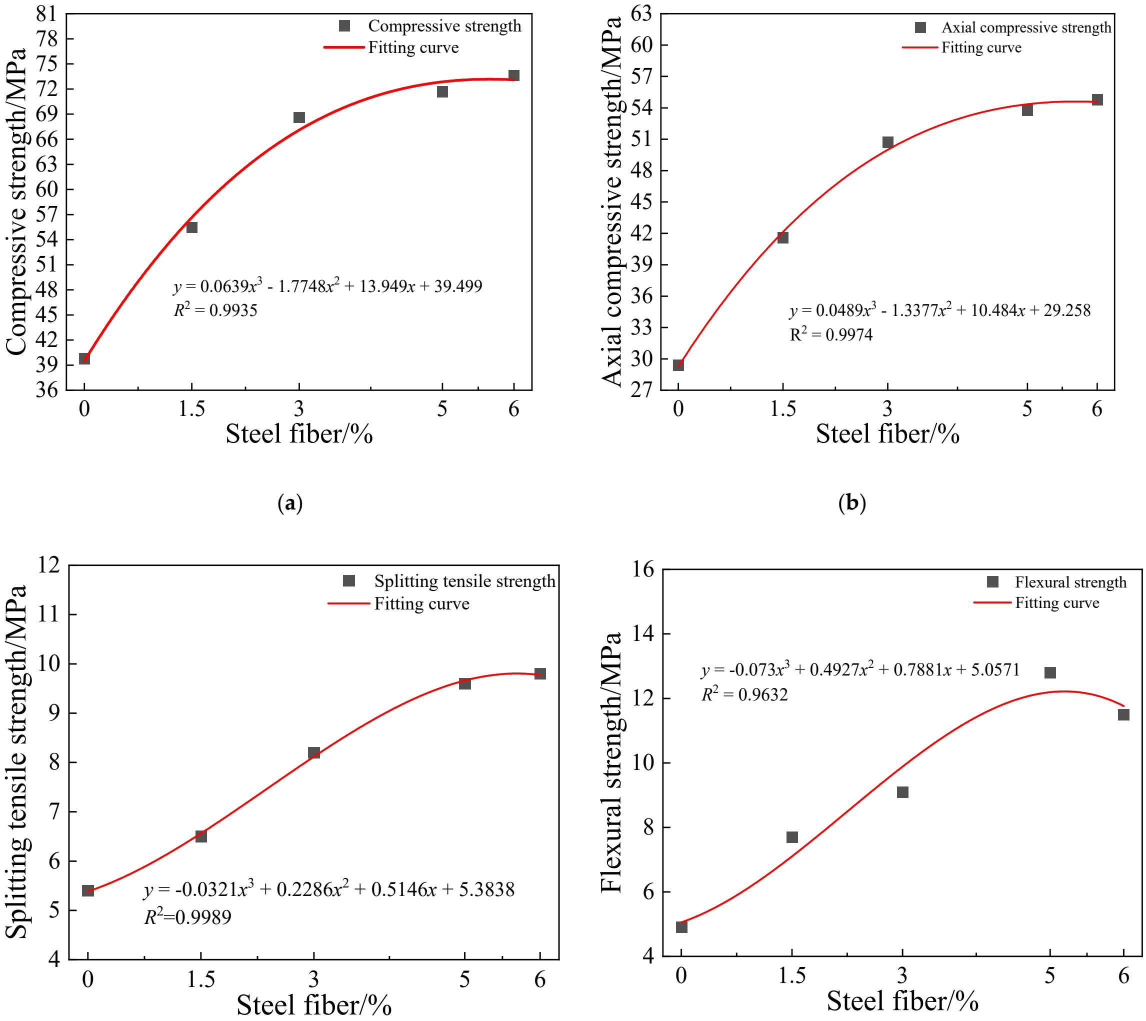
Number	Steel Fiber (%)	Ratio of Compressive Strength to Flexural Strength	
		7 d	28 d
A0	0	8.61	8.12
A1	1.5	10.58	7.21
A2	3	10.40	7.54
A3	5	7.73	5.60
A4	6	8.63	6.40

The compressive strength of brittle materials typically far exceeds their flexural strength, with the ratio often reaching several-fold to even several tens of times greater. Nonetheless, an excessively high compression ratio is not advantageous, as it can result in material that is overly rigid and prone to fragmentation. Brittle materials, such as certain types of concrete or ceramics, are characterized by their ability to withstand significant compressive loads, which is a reflection of their compressive strength. This strength is a critical parameter in applications where the material is subjected to compressive forces. Conversely, the flexural strength of these materials is considerably lower, which pertains to their resistance to bending or flexing forces. However, while a high compressive strength is generally desirable, it is essential to maintain a balanced material property profile. A compression ratio that is too high can lead to drawbacks such as increased hardness and friability. Friability can compromise the material's durability and integrity, making it more susceptible to cracking or breaking under stress.

In summary, while the compressive strength of brittle materials is a critical parameter, it must be considered within the context of the material's overall property profile.

4.2.5. Relationship between Steel Fiber Volume Fraction and Mechanical Properties

Figure 17 illustrates the relationship between the volume fraction of steel fibers and the mechanical properties of concrete at a curing age of 28 days. The data presented in the figure indicate a positive correlation between the content of steel fibers and the mechanical properties of the concrete, up to a certain threshold. Specifically, the cubic compressive strength, axial compressive strength, splitting tensile strength, and flexural strength all exhibit an incremental trend with the increase in the volume fraction of steel fibers from 0% to 5%. However, a saturation point is observed beyond this threshold. When the volume fraction of steel fibers reaches 6%, the cubic compressive strength, axial compressive strength, and splitting tensile strength plateau, suggesting that further increases in fiber content do not yield significant enhancements in these properties. Moreover, an inverse relationship is noted for flexural strength, where an excess of steel fibers—beyond a volume fraction of 5%—results in a decline in this property.



(**a**) (**b**)

(**c**) (**d**)

Figure 17. Relationship between steel fiber volume fraction and mechanical properties: (**a**) compressive strength and fiber volume fraction; (**b**) axial compressive strength and fiber volume fraction; (**c**) splitting tensile strength and fiber volume fraction; and (**d**) flexural strength and fiber volume fraction.

This finding underscores the importance of an optimal steel fiber content to maximize the mechanical performance of concrete. The results highlight a critical inflection point in the fiber volume fraction, beyond which the benefits of additional steel fibers are negated, potentially due to the fibers' clustering or impaired integration within the concrete.

The prediction equations for cubic compressive strength, axial compressive strength, split tensile strength and flexural strength are shown in expressions (1), (2), (3), and (4), respectively.

$$y = 0.0639x^3 - 1.7748x^2 + 13.949x + 39.499 \tag{1}$$

$$y = 0.0489x^3 - 1.3377x^2 + 10.484x + 29.258 \tag{2}$$

$$y = -0.0321x^3 + 0.2286x^2 + 0.5146x + 5.3838 \tag{3}$$

$$y = -0.073x^3 + 0.4927x^2 + 0.7881x + 5.0571 \tag{4}$$

4.2.6. Comparative Analysis of Self-Compacting Concrete with Extra-Short Extra-Fine Steel Fibers and Self-Compacting Concrete with Ordinary Steel Fibers

To better reflect the advantages and disadvantages of extra-short extra-fine steel fibers, a comparative analysis is made by searching the related literature.

Liu et al. [38] carried out a comprehensive performance evaluation of steel fiber-reinforced concrete incorporating 60% fly ash, utilizing steel fibers with a length of 35 ± 3 mm. The fibers were incorporated at various volume fractions—0.25%, 0.50%, 0.75%, and 1.00%—to assess their impact on the concrete's workability and mechanical properties in both its fresh and hardened conditions. The investigation encompassed parameters such as compressive strength, splitting tensile strength, flexural strength, and the characteristics of axial compressive deformation. The following conclusions were drawn from their research:

(1) Self-compacting concrete (SCC) prepared with high levels of fly ash (50%, 60%, and 70%) exhibits generally improved workability in the fresh state, whereas there is an inverse relationship between the mechanical properties and the content of fly ash;
(2) The workability of SCC deteriorates sharply when the volume fraction of steel fibers exceeds 0.75%. This indicates that a volume fraction of 0.75% is a critical threshold for workability in steel fiber-reinforced SCC with a high fly ash content;
(3) The incorporation of steel fibers does not significantly affect the compressive strength of SCC containing a high level of fly ash, but it markedly enhances its splitting tensile and flexural properties. The addition of 1.00% steel fibers can lead to a 22% and 58% increase in splitting tensile strength and flexural strength, respectively, compared to SCC without steel fibers;
(4) Regarding the axial compression deformation characteristics, the introduction of steel fibers, particularly in SCC containing 60% fly ash, results in an increase in strain energy ($V\varepsilon$) and relative toughness (Γ). The optimal $V\varepsilon$ and Γ under axial compression deformation are achieved with a 0.25% steel fiber addition.

Hazrina et al. [39] conducted a study to assess the impact of incorporating steel fibers on the mechanical properties of self-compacting concrete (SCC) reinforced with steel fibers. The fibers utilized had a volume fraction of 1%, a length of 35 mm, and a diameter of 0.55 mm. The investigation encompassed a comprehensive analysis of both the rheological and mechanical characteristics of traditional SCC and its steel fiber-reinforced counterpart. The findings can be summarized as follows:

(1) The incorporation of 1% steel fibers led to a reduction in the workability of SCC, as evidenced by decreased slump flow diameter and an increase in T500 flow time, indicating a more viscous mix. Despite the decrease in workability, the SCC with steel fibers (SCCFibre) maintained an acceptable level of flow and fill ability, complying with the EFNARC guidelines for self-compacting properties;
(2) The compressive strength of SCCFibre was found to be lower than that of plain SCC, with a notable reduction, at 28 days, of approximately 18%, which marginally decreased to 7% at 42 days. This suggests that the presence of steel fibers affects the compressive performance of the mix;

(3) In contrast to the compressive strength, the addition of steel fibers significantly improved the splitting tensile strength by 54.72%, demonstrating the fibers' effectiveness in enhancing the concrete's resistance to crack propagation and improving its ductility;

(4) The flexural strength of SCCFibre also showed a marked increase, with the ultimate load capacity more than doubling compared to plain SCC, indicating an enhanced ability to resist bending moments and prevent brittle failure.

An analysis of the findings from these two studies underscores the rationale for utilizing extra-short extra-fine steel fibers in concrete reinforcement. Despite their potentially lower mechanical properties compared to ordinary steel fibers, these extra-short extra-fine steel fibers demonstrate a marked enhancement in concrete's resistance to cracking and flexural performance at elevated fiber concentrations, without compromising compressive strength. Moreover, this specific steel fiber aspect ratio maintains the concrete's workability while contributing to superior mechanical properties, particularly in regions where higher fiber dosages are required and ordinary fibers falter. Consequently, the selection of extra-short extra-fine steel fibers is rooted in their synergistic benefits, augmenting both the durability and mechanical integrity of concrete, especially within the context of substantial fiber incorporation.

4.3. Synergistic Effect of Extra-Short Extra-Fine Steel Fibers with Fly Ash

The combination of extra-short extra-fine steel fibers with fly ash may exhibit potential synergistic effects in concrete due to the complementary benefits each material contributes to the mixture. Here is a brief explanation of the potential synergies:

1. Improvement in mechanical properties: The addition of extra-short extra-fine steel fibers enhances the concrete's tensile and flexural strength by providing crack bridging and reducing the risk of brittle failure. Fly ash, due to its pozzolanic properties, can improve the concrete's long-term strength and durability;
2. Sustainability: Both steel fibers and fly ash are considered sustainable materials. Fly ash is a by-product from coal combustion and its use in concrete reduces waste and environmental impacts. Steel fibers, being durable and long-lasting, contribute to the sustainability of the structure by reducing maintenance and replacement costs;
3. Workability: Although the addition of steel fibers can affect the workability of the concrete, the spherical nature of fly ash particles can help to maintain or even improve the flow and workability of the fresh concrete.

5. Conclusions

This study thoroughly investigated the performance impact of extra-short extra-fine steel fibers in self-compacting concrete (SCC) with single fly ash incorporation, reaching the following professional conclusions:

(1) Workability adjustment: The incorporation of steel fibers has a negative effect on the flowability, but the cohesion is significantly improved. It can be effectively compensated by optimizing the mixing process and adjusting the mix proportions. For instance, reducing the aggregate content and increasing the binder content can mitigate the loss of fluidity. Concrete with a steel fiber content of up to 3% maintains good flowability and bleeding resistance. Moreover, high volumes of steel fibers still ensure the comprehensive mechanical performance of the concrete;

(2) Mechanical properties enhancement: The mechanical properties of concrete, including compressive strength, split tensile strength, and flexural strength, were markedly enhanced with the increased addition of extra-short extra-fine steel fibers. At a fiber content of 5%, the concrete exhibited optimal mechanical performance at 28 d, with respective strength values of 71.7 MPa, 9.6 MPa, and 12.8 MPa—an impressive 80.1%, 77.8%, and 161.2% increase, respectively, over no-fiber concrete. These results underscore the significant contribution of appropriately proportioned steel fibers to the structural integrity of concrete and highlight the benefits of utilizing higher dosages of extra-short extra-fine steel fibers. The reinforced concrete demonstrated supe-

rior ductility and toughness, maintaining load-bearing capacity post-cracking under maximum service loads, with this capability further amplified by incremental fiber content increases;

(3) Fiber content effect analysis: When the steel fiber content exceeds 3%, the rate of improvement in the concrete's mechanical properties slows down, especially when the content reaches 5%, after which the increase in flexural strength becomes negligible. This may be due to the excessive fiber content leading to increased heterogeneity within the concrete, affecting the overall performance of the concrete;

(4) Fiber dispersion: Due to their small size and high content, extra-short extra-fine steel fibers can achieve good dispersion within the concrete, which helps to improve the uniformity and toughness of the concrete, thereby enhancing its ductility and crack resistance to some extent;

(5) Based on the study's findings, the following simplified conclusions guide the selection of steel fibers for concrete applications: (a) To reduce cracking and shrinkage, use extra-short extra-fine steel fibers for their uniform dispersion and larger surface area; (b) For strength improvement with low fiber content (under 3%), choose ordinary steel fibers. For higher fiber content (above 3%), opt for extra-short extra-fine steel fibers; (c) To increase toughness, select extra-short extra-fine steel fibers due to their even distribution in the concrete.

In summary, this research confirms the potential of extra-short extra-fine steel fibers in optimizing the mechanical performance of self-compacting concrete and provides important reference data for the mix-proportion design of SCC in practical engineering applications. Future studies can further explore the optimal fiber content and the synergistic effects with other supplementary cementitious materials to maximize the performance of concrete.

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