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Mechanical Behavior of Refined SCC with High Admixture of Hybrid Micro- and Ordinary Steel Fibers

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Abstract: The addition of steel fiber to self-consolidating concrete (SCC) may considerably prolong concrete cracking time and improve its deforming performance. Current studies mainly apply high content micro-steel fibers to improve the mechanical performance of SCC whilst assuring its workability, however, there are still very few studies concerning the influence of a mixture of a high content of micro-steel fibers with ordinary steel fibers on the performance of SCC. Thus, this paper conducted experimental studies on micro-steel fiber and ordinary-sized steel fiber hybrid reinforced self-consolidating concrete (MOSCC). Plain self-consolidating concrete (PSCC), micro-steel fiber reinforced self-consolidating concrete (MSCC), and ordinary-sized steel fiber reinforced self-consolidating concrete (OSCC) are proposed for comparison with MOSCC in respects of workability and mechanical performance. Test results show that the hybrid micro-steel fiber and ordinary steel fiber highly enhance the compressive strength, flexural strength, and ductility of SCC as well as maintaining its workability. This paper provides reference to the improvement of the mechanical performance of SCC material and the enhancement of crack resistance of concrete structures.

Keywords: self-consolidating concrete; micro-steel fiber; high admixture; mechanical performance

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1. Introduction

Self-consolidating concrete (SCC) features high flowability, uniformness, and stability, in which uniform compaction can be achieved due to gravity without vibrating during construction [1]. Owing to the fine workability, SCC is extensively used in structures with complex forms and densely arranged reinforcement. However, SCC has disadvantages such as early shrinkage and cracking, and poor durability. Hence fibers, particularly steel fiber, are considered to mix into the SCC to resolve the above problems whilst maintaining its working performance.

Steel fibers have the potential to improve the mechanical property and deformation performance of concrete. This can be utilized to prohibit the generation and extension of micro-cracks in concrete whilst reducing the self-contraction deformation of concrete by its bridging and cracking resisting function. Researchers first revealed that a single ordinary type of steel fiber can effectively improve the mechanical property and durability of SCC. M. Akbari et al. [2] studied the impact on the compressive strength of SCC by the addition of volume fraction of 0.1%, 0.2%, and 0.3% steel fiber 33mm in length; and the test results show that the concrete compressive strength increased with increment of the volume fraction of fiber. Athiyamaan V [3] added micro steel fiber with a hooked end with the length-diameter ratio of 60 by a proportion of 0.25%, 0.50%, 0.75%, and the test result show that admixture of steel fiber greatly improved the bending resistance of SCC and inhibited the development of cracks, prevented fragile damage to the concrete, and improved its strain performance. Sahith Gali [4] found that the addition of a volume fraction of 0.75% (diameter of 0.75 mm, length of 60 mm) fiber steel with a hooked end can improve SCC, and the experiment results show that admixture of steel fiber improved rupture resistance of SCC, and also improved its shear capacity. Gisele et al. [5] mixed SCC with an addition of 0.25%, 0.5%, and 1% of steel fiber of diameter 0.75 mm respectively, and used V-funnel test and J-ring test to evaluate the slump ratio, flow velocity, and plastic viscosity of the mixture, and concluded that concrete bending was in proportion to the addition amount of fiber.

In their study into improving the properties of SCC with hybrid fibers, Cong Zhang [6,7] improved the mechanical behavior of an SCC beam by mixing steel fibers of 60 mm length, 0.75 mm diameter, and polypropylene fiber of different sizes, and revealed that steel fiber can significantly improve the bending resistance of concrete. Monteiro et al. [8] studied the mechanical properties of SCC with added steel fiber (of length 30 mm, diameter 0.62 mm and length 60 mm, diameter 0.75 mm), polypropylene fiber, and other different admixture of fiber; the test result shows that steel fiber is more outstanding than polypropylene fiber with respect to the crack resistance property of the concrete. Nabeel [9] improved the mechanical performance of polymer concrete by adding steel fibers of 13 mm length (diameter of 0.2 mm) and 6 mm length (diameter of 0.2 mm) into the volume admixture of 2%, while Jiaqing Wang et al. [10] pointed out that the mixture of various steel fibers and polypropylene fibers significantly reinforced rubber concrete. Generally, steel fibers more greatly enhance SCC than flexible fibers such as polypropylene fibers.

Most researchers tend to improve the performance of SCC by adding hybrid steel fibers. Burcu Akcay [11] showed that micro-steel fibers of various lengths and diameters, uniformly scattered in the SCC without any blocking, improved the toughness of the concrete. Deeb et al. [12] added micro-steel fibers (length of 6 mm and diameter of 0.16 mm) at 5% volume admixture together with steel fibers (length of 13 mm, diameter of 0.16 mm) at 1% volume admixture into SCC; the test results showed that a higher content of micro-steel fibers in the mixture can generate SCC with a satisfactory flowability. Dimas et al. [13–15] mixed straight-ended steel fibers (length of 12 mm and diameter of 0.18 mm) and hook-ended steel fibers (length of 5 mm, diameter of 0.55 mm) into SCC, further proving that hybrid steel fibers largely promote the compression strength, tensile strength, and bending deforming performance of SCC. Pajak and Ponikiewski [16] point out that the use of steel fibers improves flexural and residual strength, but may not offer improvements in compressive strength or in elastic modulus. Khaloo et al. [17] also verified that the negative effects of the incorporation of steel fibers on fresh state properties, as well as on compressive strength, are highly dependent on the incorporated volume. Above all, the current studies prove that steel fibers can significantly improve the mechanical properties of ordinary concrete, polymer concrete and SCC. However, the dosage level of steel fibers is limited due to the lower workability of higher admix steel fiber reinforced SCC. Furthermore, improving the mechanical behavior of SCC by increasing the content of steel fibers is less discussed.

Hence, this study aims to demonstrate the feasibility of using a combination of micro-steel fibers and ordinary steel fibers to reinforce SCC with agreeable workability by means of a laboratory testing program and statistically comprehensive methods.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Cement

Portland cement with a strength grade of 42.5 (produced by Red Star construction material company Co., Ltd., Chongqing, China) was adopted. Its physical mechanical properties are presented in Table 1.

Table 1. Cement physical mechanical properties.

Fineness (Remains on the 80 µm Square Sieve) (%)	Consumption of Water with Standard Viscosity (%)	Hardening Time (h:min)		Compressive Strength (MPa)		Flexural Strength (MPa)		Stability (Boiling Method)
		initial hardening	final hardening	3 d	28 d	3 d	28 d	
0.0	27.6	2:25	3:45	28.4	56.2	5.9	9.6	acceptable

2.1.2. Fly Ash

Fly ash is grade I fly ash with a specific surface area of 420 m^3/kg, density of 2.42 g/cm^3, burn loss of 2.48%, and content of 3.82% Fe_2O_3, 2.72% CaO, 0.82% MgO, 29.09% Al_2O_3, and 53.36% SiO_2. For SCC, in order to improve performance, grade I fly ash is prioritized, and grade II fly ash can also be used; the water demand ratio should not exceed 100%.

2.1.3. Aggregate

The fine aggregate is ordinary medium sand, with a fineness modulus of 2.6 and a mud content of 3.3%. Coarse aggregate: crushed limestone, needle sheet particle content of 9.7%. Mix the coarse aggregates of 5~10 mm and 10~16 mm at a mass ratio of 1:1 and use the mixture.

2.1.4. Steel Fiber

The ordinary-sized steel fibers in this research are made by the sheet steel shearing method, as shown in Figure 1a. The micro-steel fibers are ultra-short & ultra-fine steel fibers made by the melting and extraction method shown in Figure 1b. Both types of steel fiber are produced by Daotuo Construction Material Co. Ltd., Chongqing, China. The selected steel fibers are mixed into the concrete volume term. The ordinary-sized steel fiber and micro-steel fiber are denoted as OS fiber and MS fiber respectively, and their mechanical properties are listed in Table 2.

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

Figure 1. The OS and MS fibers. (**a**) Ordinary-sized steel fiber (OS). (**b**) Micro-steel fiber (MS).

Table 2. Mechanical properties of steel fibers.

Types of Steel Fibers	Length/mm	Diameter/mm	Length-Diameter Ratio	Density (t/m^3)	Elastic Modulus (GPa)	Tensile Strength (MPa)
Ordinary steel fiber	35	0.9	39	7.8	210	850
Micro-steel fiber	6	0.2	30	7.8	210	>850

2.1.5. Additive

The water reducer was made with a BASF F10 poly-carboxylic acid powder. After adding the water-reducing agent, a completely unsegregated plaster mixture can be produced, and F10 can reduce mixing, quickly cure, increase the fluidity of the concrete, and improve the slump. After multiple tests to determine the quality of the cementing material, 0.18% was selected as the amount of incorporation. The water used was tap water from the laboratory of Chongqing Jiaotong University.

The target compressive strength of the SCC in this research was 40 MPa. The SCC mixture was designed as shown in Table 3.

Table 3. Mixture design of SCC with steel fibers.

SN	Cement (kg)	Water (kg)	Fly Ash (kg)	Coarse Aggregate (kg)	Fine Aggregate (kg)	Water Reducer (%)	Addition of Steel Fiber (%)
P-0	1	0.41	0.43	1.68	1.68	0.16%	0
OS1	1	0.41	0.43	1.68	1.68	0.16%	1%OS
OS2	1	0.41	0.43	1.55	1.55	0.16%	2%OS
MS6	1	0.40	0.44	0.98	0.98	0.16%	6%MS
OS1 + MS6	1	0.40	0.44	0.98	0.98	0.16%	1%OS + 6%MS
OS2 + MS6	1	0.39	0.44	0.98	0.98	0.16%	2%OS + 6%MS

Note: P-0 is plain self-consolidating concrete, OS is shear type ordinary steel fiber, MS is melt-drawn type ultra-short ultra-fine steel fiber; the volumes of steel fiber are noted by 1%, 2%, and 6% in the manuscript, which represents the mix ratio of steel fibers in SCC. 1%, 2%, and 6% steel fiber contents are represented by 1, 2, and 6 respectively, e.g., OS1 + MS6 stands for 1% ordinary steel fiber plus 6% ultra-short ultra-fine steel fiber mixed concrete.

The fresh concrete and steel fibers are mixed in a concrete mixer. The material container and mixing blade were wetted with a small quantity of water before mixing the weighed cement, sand particles, fly ash, and additives. A fiber concrete disperser can be applied in case of a large amount of steel fibers.

2.2. Sample Preparation

In the fresh state, tests to determine the flow spread and the flow rate using the Abrams cone were determined by ASTM C1611 [18], and passing ability by the J-ring through ASTM C1621 [19]. Fresh state tests were performed within 15 min after the complete homogenization of the mixtures. Considering the time after homogenization, each test was performed with a time-space of 2 min between them. The test results are illustrated in Figure 2a,b. Experimental data are listed in Table 4.

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

Figure 2. Concrete fluidity test. (**a**) Slump flow test. (**b**) J-ring extension.

Table 4. Slump extension diameter and J-ring extension.

Group No.	Fiber Length	Content of Fiber	Slump Extension (mm)	T_{500}(s)	J-Ring Extension (mm)
P-0	0	0	610	3.2	570
OS1	35 mm	1% OS	590	3.6	550
OS2	35 mm	2% OS	580	3.9	545
MS6	6 mm	6% MS	575	4.7	525
OS1 + MS6	35 mm + 6 mm	1% OS + 6% MS	565	5.1	505
OS2 + MS6	35 mm + 6 mm	2% OS + 6% MS	550	5.6	495

Through the analysis of several amounts of micro-steel fibers, Khayat et al. [20] gathered results that support the results in this research, indicating that higher amounts of fiber increase the flow rate linearly. Contrary to this study, the flow rate varied with respect to the amount.

2.3. Test Methods

In this research, the mechanical behavior of SCC is presented by cube compressive strength, flexural strength, axial compressive strength, axial compressive stiffness and bending toughness; thus, cube specimens, beam specimens, and cylindrical specimens were prepared for the corresponding tests. Six groups of a specimen of PSCC, OSCC, and MOSCC were initially tested and studied. The influences of the addition of steel fibers on the SCC were compared and evaluated. The amounts of the specimen under each design solution are 18 specimens for respective cube compressive strength, flexural strength, axial compressive strength, and bending toughness tests, and 36 specimens for axial compressive stiffness tests. The total number of specimens was 108. The specimen sizes and numbers are detailed in Table 5.

Table 5. Specimen size and amount.

Test Type	Specimen Size (mm)	Number of Specimens	Total Numbers of Specimens
Cube compressive strength	100 × 100 × 100	3	18
Flexural strength	100 × 100 × 400	3	18
Axial compressive strength	100 × 100 × 300	3	18
Axial compressive stiffness	100 × 100 × 400	3	18
Bending toughness	100 × 100 × 300	6	36

2.3.1. Cube Compressive Strength Test

The most important parameter to elevate concrete material property is compressive strength and flexural strength [21]. The compressive strength was tested by following the Chinese Standard GB/T 50081-2019 [22]. A cube specimen of dimension 100 mm × 100 mm × 100 mm was taken, and three similar specimens made and the form removed after 24 h. The cube specimens and beam specimens were prepared and cured for 28 days. The specimen was placed with its axial core perpendicular to the center of the pressing plate and the pressing plate was adjusted close to and above the upper surface of the specimen without touching. Activating the testing machine for pre-pressing and loading speed in pre-pressing takes 0.5 MPa/s for the physical alignment adjustment and stability adjustment of the compressed. After completion of prepressing, add loading at a speed of 0.1 mm/min on the specimen until it is damaged, and then discharge loading generally. The loading process is illustrated in Figure 3a,b.

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

Figure 3. Cube compressive strength test schemes. (**a**) PSCC. (**b**) MOSCC-OS1 + MS6.

The compressive results of the specimen shall be calculated as per following formula:

$$f_{cc} = \frac{F}{A} \quad (1)$$

where f_{cc} is the compressive strength (MPa) of steel fiber reinforced SCC, F is the ultimate load (N), A is the average value of compression areas of upper and lower surfaces of specimen (mm^2).

2.3.2. Flexural Strength Test

The flexural strength test results were taken according to Chinese Standard GB/T 50081-2019 [22]. The specimen takes dimensions of 100 mm × 100 mm × 400 mm. The test was conducted with the hydraulic universal testing machine, as shown in Figure 4a. Length axle of the specimen is perpendicular to the support circular axle. Loading is added at a constant speed of 50 N/s. Place the specimen on the test machine with its length axle perpendicular to the support circular axle, with spacing between the lower two circular supports at 0.3 m, with constraint being fixed hinge and universal rolling hinged support. Activate the test machine and then pre-press the specimen with a load of 1 KN, check the evenness of the specimen position to ensure test progress is standard and safe. Continue adding load with a loading speed of 0.06 MPa/s before the appearance of initial damage to the specimen. Once a crack appears in the specimen change the loading mode and control the specimen by displacement, and continue loading until damage to the specimen. The loading process was illustrated in Figure 4b.

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

Figure 4. Flexural strength test schemes. (**a**) Flexural strength test. (**b**) Flexural strength test specimens.

Specimen flexural strength in MPa is calculated by the following formula:

$$f_f = \frac{PL}{bh^2} \tag{2}$$

where f_f is the flexural strength of steel fiber reinforced SCC (MPa), P is the damaging load imposed on the middle of the specimen at flexural (N), L is the support space (mm), b is the specimen height (mm), h is the specimen width (mm).

2.3.3. Axial Compressive Strength

Non-standard specimen of dimensions 100 mm × 100 mm × 300 mm was used for testing, and the conversion coefficient is 0.95. The loading process is illustrated in Figure 5.

Figure 5. Axial compressive strength test.

The axial core compressive strength of the concrete specimen is calculated as per the following formula:

$$f_{cp} = \frac{F}{A} \tag{3}$$

where f_{cp} is the axial core compressive strength (MPa), calculated result accuracy is up to 0.1 MPa, F is the damaging load of specimen (N), A is the bearing area of the specimen (mm^2).

2.3.4. Axial Compressive Stiffness

The strain sheet is attached to the specimen with a side hole diameter of less than 5 mm and a depth of less than 2 mm. Considering the error caused by unevenly distributed aggregates, tighten the attachment of the strain sheet with a pasting rod at the bilateral centers of the specimen, and the center lines on the sides should be in alignment, as in Figure 6a. After the pasted places are dried, place the specimen on the bearing as per the specification. Prepare to add load on the universal testing machine. The static pressure elastic modulus is tested by the loading manner shown in Figure 7. When loading reaches an initial loading value of 0.5 MPa, stay for 60 s before the next load, until obtaining 1/3 standard loading for the axial core compressive strength of concrete of the corresponding type. Repeat the above steps more than five times and record the bilateral-sided strain values of the specimen from the final time, from initial loading up to the standard loading, as in Figure 6b.

(a) (b)

Figure 6. Axial compressive stiffness test schemes. (**a**) Strain gauge contacts. (**b**) Axial compressive stiffness test experimental setup.

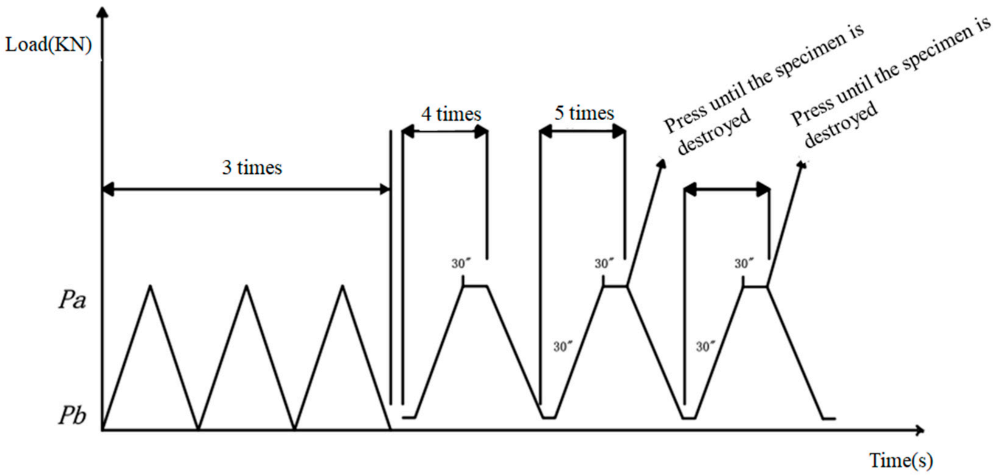


Figure 7. Loading cycle schematic.

Concrete axial compressive stiffness shall be calculated by the following formula:

$$E_c = \frac{F_a - F_0}{A} \times \frac{1}{\Delta n} \tag{4}$$

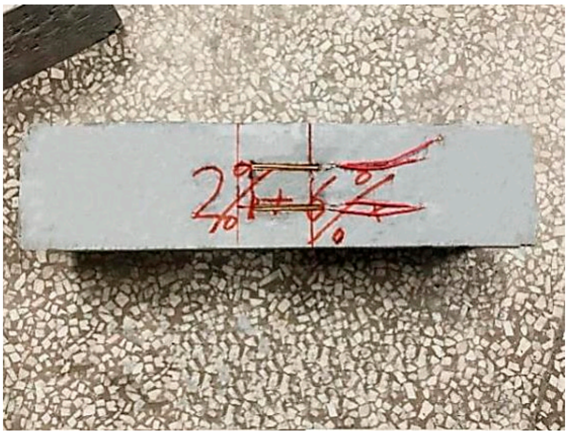
where E_c is the concrete axial compressive stiffness (MPa), F_a is the standard load (N) at 1/3 axial core compressive strength, F_0 is the initial load (N) at initial load of 0.5 MPa (N), A is the average bearing areas of specimen (mm^2).

$$\Delta n = \varepsilon_a - \varepsilon_0 \tag{5}$$

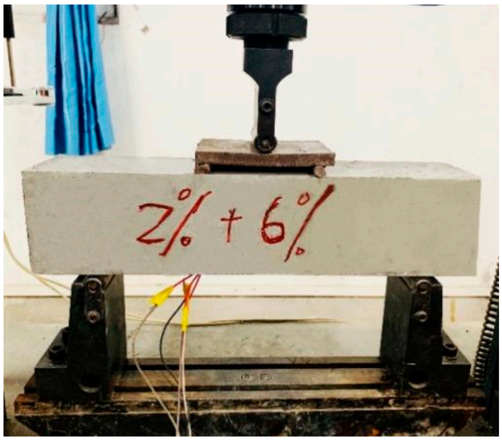
where Δn is the specimen bilateral sided average value $(\mu\varepsilon)$ in the last time from initial loading (F_0) up to standard loading (F_a), ε_a is the bilateral sided average value $(\mu\varepsilon)$ at loading up to standard load $(F_a)(\mu\varepsilon)$, ε_0 is the bilateral strain average value $(\mu\varepsilon)$, when loading increased to initial load.

2.3.5. Bending Toughness Test

As per the specification test, specimen shall take the dimension of 100 mm × 100 mm × 400 mm. Due to limited test conditions in this paper, a three-point loading method was applied [23]. The bending toughness test was carried out on a WE-100 hydraulic universal test machine, and the specimen lies on a circular support axle, as shown in Figure 8a. By loading the circular support with a constant speed of 50 N/s until rupture of the specimen, strainmeter is used to measure the deflection of the smaller beam, as in Figure 8b.



(a)



(b)

Figure 8. Bending toughness test. (**a**) Strain gauge contacts. (**b**) Flexural strength test experimental setup.

The equivalent bending toughness is calculated in the sketch, shown in Figure 9, where the ordinate is the initial crack load, the abscissa is the initial crack deflection, the initial crack point is *A*, and the area *OAD* is the initial crack toughness.

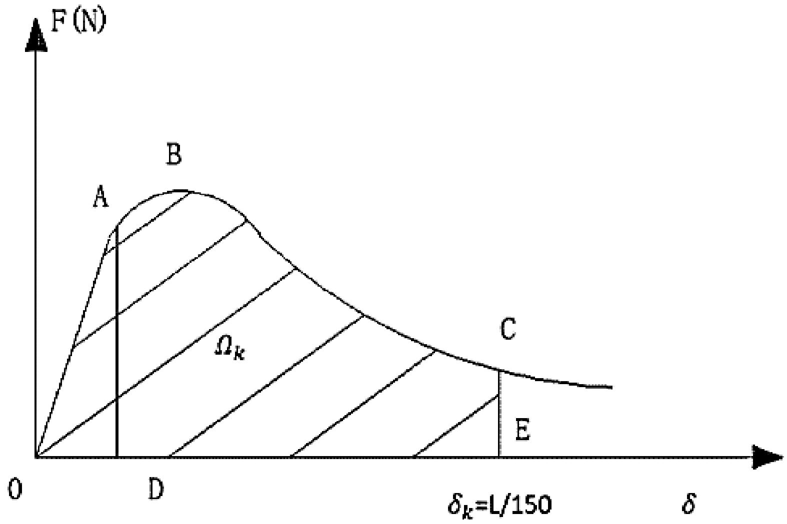


Figure 9. Equivalent bending toughness scheme.

1. Initial cracking strength at bending

Initial cracking point is *A*, the formula for the initial cracking strength calculation is shown in Formula (6).

$$f_{cr} = \frac{F_{cr} L}{bh^2} \tag{6}$$

where f_{cr} is the initial strength (MPa) of rupture resistance of steel fiber reinforced concrete, F_{cr} is the initial cracking load of the steel fiber reinforced concrete, b is height of the specimen (mm); H is width of the specimen (mm), L is the space between supports to the specimen.

2. Equivalent bending strength

The equivalent bending toughness of steel fiber reinforced concrete shall be calculated by Formula (7):

$$f_e = \frac{\Omega_k L}{bh^2 \delta_k} \tag{7}$$

where f_e is equivalent bending toughness, Ω_k areas (mm) in the load-defection curve when mid span deflection is *L/150* (N·mm), δ_k is deflection value (mm) when mid span deflection is *L/150* (mm).

3. Bending toughness ratio *Re*

The bending toughness ratio of the specimen shall be calculated by Formula (8):

$$R_e = \frac{f_e}{f_{cr}} \tag{8}$$

3. Results

3.1. Cube Compressive Strength

Figure 10a–d demonstrate the damages to the cubes of PSCC, OSCC and MOSCC.

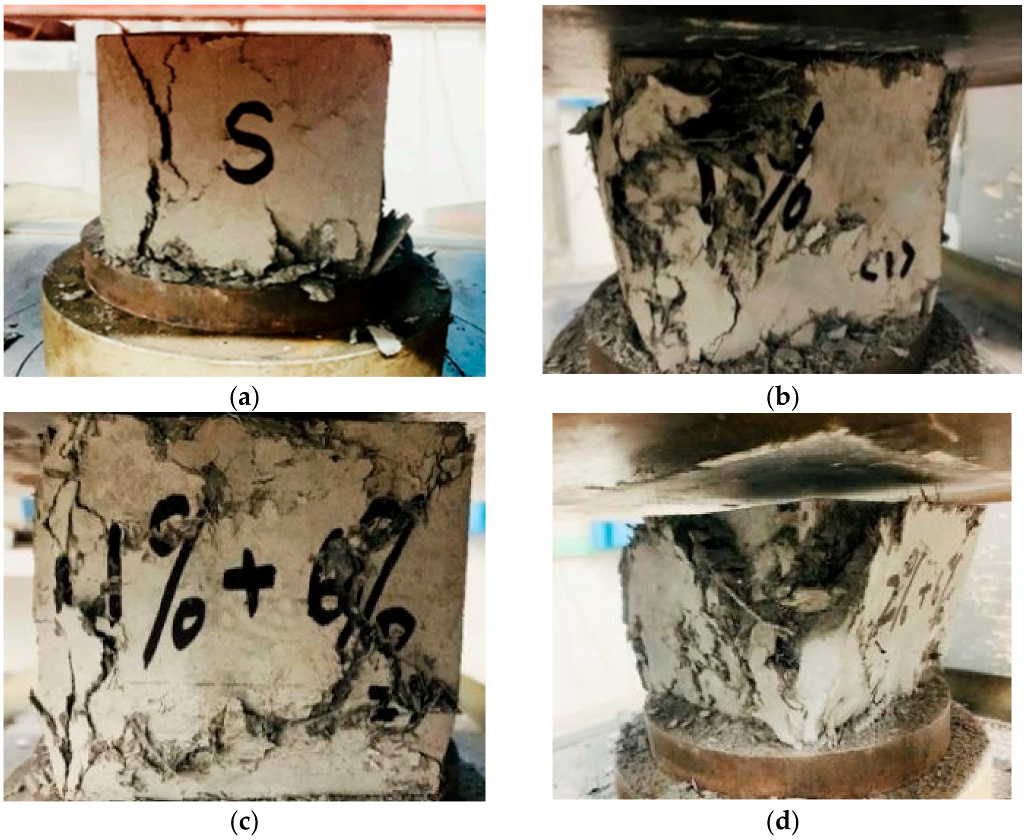


Figure 10. Damages of various SCC cube specimens. (**a**) PSCC. (**b**) OSCC-MS6. (**c**) MOSCC-OS1 + MS6. (**d**) MOSCC-OS2 + MS6.

As indicated in Figure 10, with an increase to the mixture of steel fibers, concrete spalling is slower, its bearing time is longer after spalling, and spalling is uniform. It is known that specimen 2% OS + 6% MS has a longer bearing time than that of specimen 1% OS + 6% MS observation. Namely, with a 1% increase to the long fiber, the hybrid steel fiber concrete has improved ductility. This test result shows that with an increase to the addition amount of fibers, compressive strength shows a rising trend. The compressive strength from S-0 to 1% OS materials increased considerably. However, after steel fiber is incorporated, compressive strength changes slowly and gently. That is to say, increases to steel fiber content and mixture of various fiber mixtures did not bring about an abrupt surge in compressive strength.

Table 6 shows that, compared with PSCC, a single addition of steel fiber improved the compressive strength of steel fiber reinforced SCC by 29.2%, 46.0% and 58.2% respectively, when the volume addition of ordinary steel fiber was 1% and 2%, and the volume addition of ultra-short and ultra-fine steel fiber was 6%. Compared with OSCC, compressive strength is improved by 70.0% and 87.4%, when 1% volume amount of ordinary steel fiber and 6% volume amount of ultra-short and ultra-fine steel fiber, and 2% ordinary steel fiber and 6% ultra-short and ultra-fine steel fiber in 28 d. Hence, a higher content addition of ultra-short and ultra-fine steel fiber mixed with ordinary steel fiber can considerably improve the compressive strength of SCC, as shown in Figure 11. Abukhashaba et al. [24] and Gisele C.S. et al. [5] also found a negative correlation between the amount of fibers and the mechanical strength. With an increase to the volume of steel fibers, the effect of fiber crack resistance begins to dominate. In the process of tension, after the matrix is cracked, steel fibers with greater deformability can bear the tensile force and keep the matrix cracks slowly expanding. This acts until the steel fiber is broken or pulled out from the matrix, thereby improving the compressive strength of the SCC.

Table 6. Test results of compressive strength of SCC.

SN	Fiber Content Added	Compressive Strength (MPa)	Range of Improvement	Variance σ^2
P-0	0	51.3	—	0.62
OS1	1%OS	66.3	29.2%	1.72
OS2	2%OS	74.9	46.0%	2.11
MS6	6%MS	81.2	58.2%	2.87
OS1 + MS6	1%OS + 6%MS	87.2	70.0%	2.40
OS2 + MS6	2%OS + 6%MS	96.6	88.3%	3.80

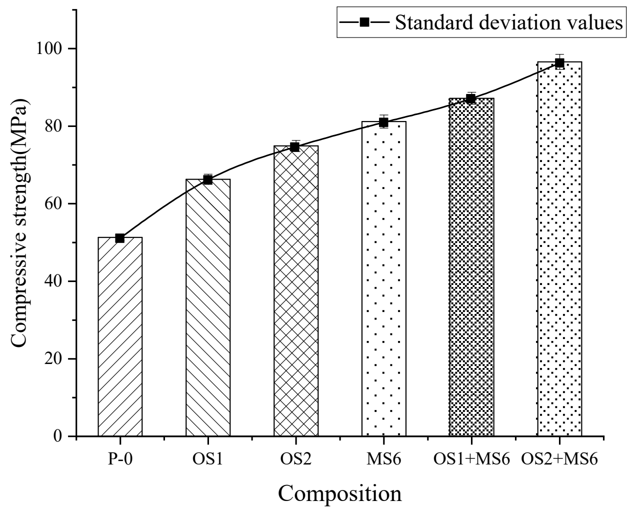
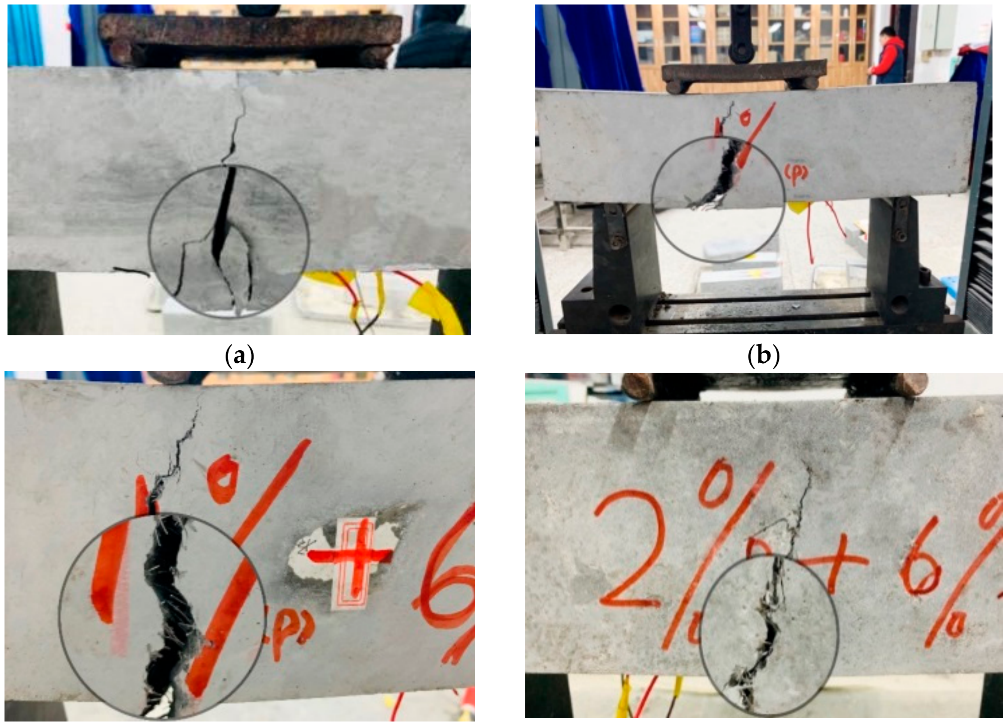


Figure 11. The compressive strength value illustration.

3.2. Flexural Strength

Figure 12a–d shows the flexural damages of specimens made of PSCC, OSCC and MOSCC.



(**a**) (**b**) (**c**) (**d**)

Figure 12. Damages of various SCC specimens. (**a**) PSCC. (**b**) OSCC-MS6. (**c**) MOSCC-OS1 + MS6. (**d**) MOSCC-OS2 + MS6.

These damage pictures show that under ultimate loads, the tensile area at the bottom edges of PSCC developed cracks in a short time under the impact of concentrated stress, with a tip-end effect. The crack extended to the top in a short time and generated a crack with a clear running direction; meanwhile, several blocks spalled in the tensile area. With a clear and loud cracking sound, the concrete block failed quickly and stopped working. The rupture-resistant concrete cube with added steel fiber, under concentrated loads at three separate points, firstly developed the main crack at a tensile area at the bottom of the example. With the increase in loading, the main crack gradually extended from the bottom in tension towards the top of the beam. With the mix ratio, the strength improvement role of these two types of steel fibers is discernible and mixture effects are sound. The flexural strength drawn from the test is shown in Table 7.

Table 7. Flexural strength test results.

SN	Content Addition of Fibers	Flexural Strength (MPa)	Range of Improvement	Elastic Modulus of Bend and Tensile ($\times 10^4$ MPa)
P-0	0	4.1	—	3. 21
OS1	1% OS	6.0	46.3%	3.50
OS2	2% OS	6.5	58.5%	3.58
MS6	6% MS	7.7	87.8%	3.61
OS1 + MS6	1% OS + 6% MS	9.8	139.0%	3.69
OS2 + MS6	2% OS + 6% MS	14.8	261.0%	3.72

Table 7 shows that, when compared with ordinary SCC, for concrete with a single addition of steel fiber, the flexural strength of the steel fiber reinforced SCC is improved by 46.3%, 58.5% and 87.8% when the content of added ordinary steel fiber reaches 1% and 2% respectively, and when the added content of ultra-short and ultra-fine steel fiber volume addition reaches 6%. Compared with PSCC, the flexural strength of SCC is improved by

139.0% with the volume addition of 1% mixture steel fibers and volume addition of 6% ultra-short and ultra-fine steel fiber, and by 261.0% with the volume addition of 2% ordinary steel fiber and volume addition of 6% of ultra-short and ultra-fine steel fiber. Denesh [25] found similar results. Figure 13 demonstrated that the volume addition of steel fiber is in proportion to the flexural strength of concrete. The results are similar to those found by Ponikiewiski [26]. Compared with PSCC, the flexural strength of SCC almost doubled with a content of 1% volume addition of ordinary steel fiber and 6% ultra-short and ultra-fine mixture steel fiber. With a volume addition of 2% ordinary steel fiber and volume addition of 6% ultra-short and ultra-fine steel fiber, the strength improvement soared. This kind of mixing method greatly improved the flexural strength of SCC. The volume addition of steel fiber can improve the tensile elastic modulus of steel fiber reinforced SCC whilst generating minor impact.

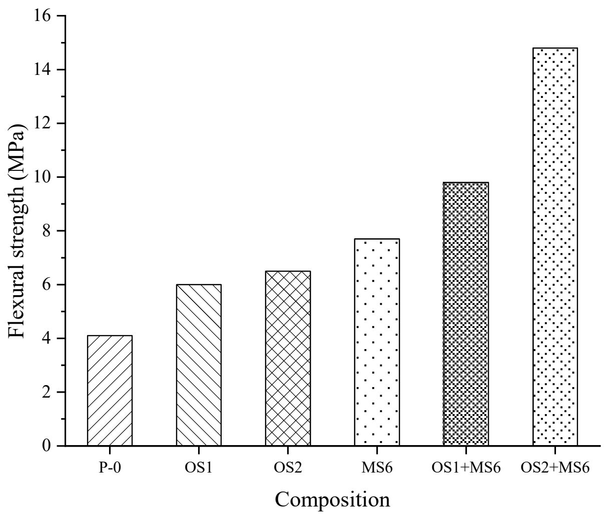


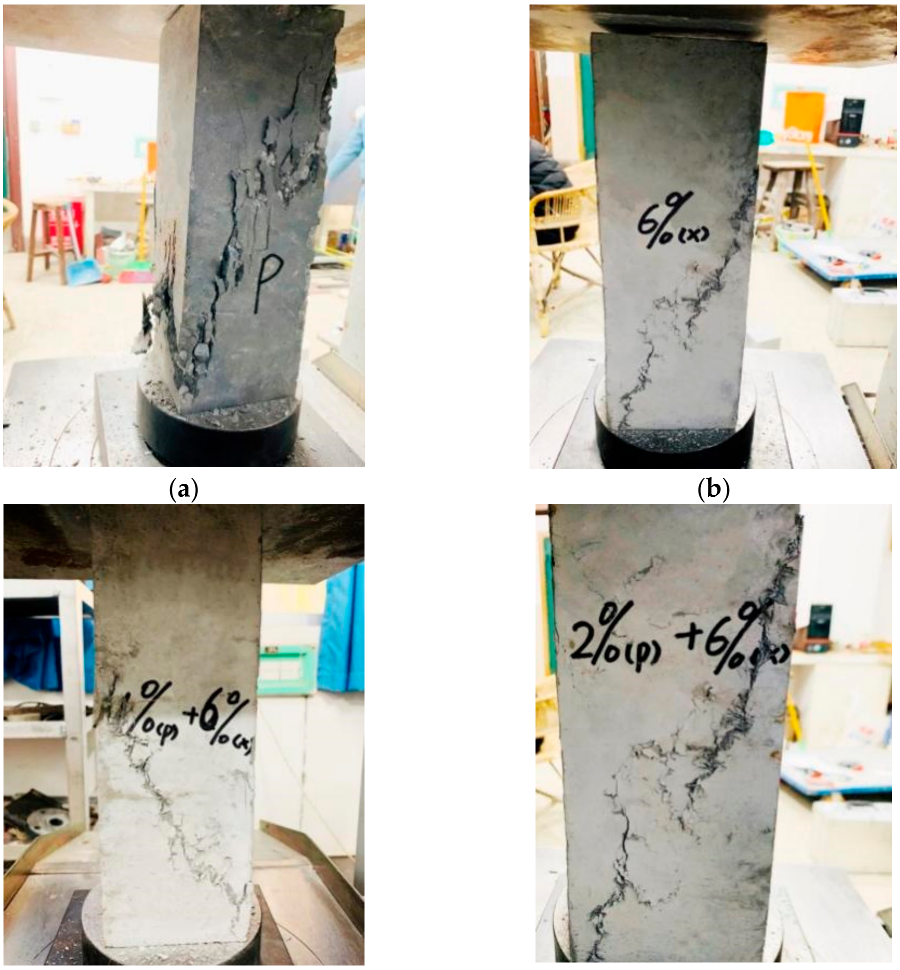
Figure 13. Bend tensile elastic modulus illustration.

3.3. Axial Compressive Strength

Compressive loading on the axial core of rectangular specimens. Figure 14a–d demonstrates the damage to specimens with different additions of steel fibers.

These pictures of damage to the axial core of SCC show that in the axial core loading test, the concrete developed degrees of inclined cracks. In the concrete cube with added steel fiber the cracks started at 2/3 height of the concrete, with 1% OS + 6% MS generating the finest crack, and no discernible fine cracks appeared surrounding the main crack. With the addition of 2% OS + 6% MS steel fiber, the inclined crack ran in a diagonal direction and generated the longest crack. The specimen with added steel fiber demonstrated notable plasticity, and this specimen was not damaged and continued bearing loads, without emitting the clear and loud rupture sound of PSCC at the moment of damage.

Figure 15 shows that the volume modulus of steel fiber is in proportion to the compressive strength of the axial core of the SCC cube, and that any addition of ordinary or a mixture of steel fiber may improve the compressive strength of the axial core of concrete. During the stress process of SCC, the addition of steel fibers can change the stress form of the text block, from concentrated stress to dispersed stress. The restraint of steel fibers can effectively inhibit the generation of micro-cracks and increase the propagation of micro-cracks, prolonging the cracking time of the test block, thereby increasing the energy absorbed by the SCC during failure, increasing its strain energy and relative toughness. Concrete for foundations with hoops and stirrups can be achieved by adding two types of steel fibers in random distributions, and a mixture of steel fibers can further develop these advantages.



(**a**) (**b**) (**c**) (**d**)

Figure 14. Axial core compressive strength test. (**a**) PSCC. (**b**) OSCC-MS6. (**c**) MOSCC-OS1 + MS6. (**d**) MOSCC-OS2 + MS6.

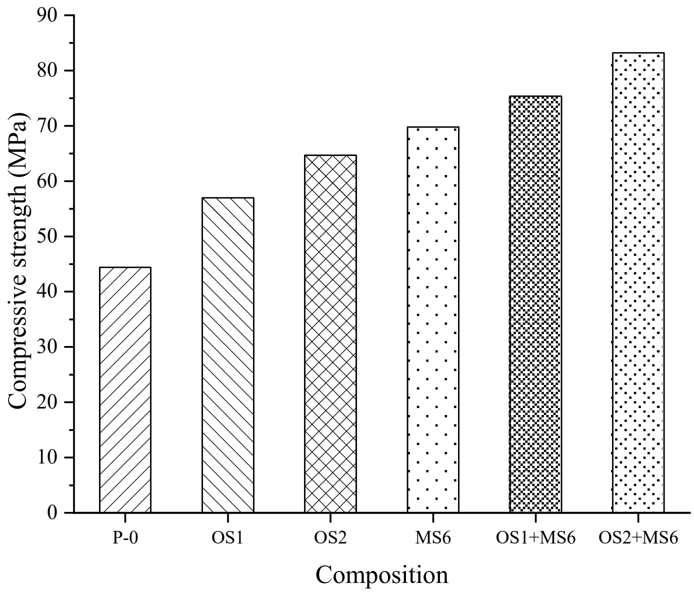


Figure 15. Axial core compressive strength illustration.

3.4. Axial Compressive Stiffness

The test shows that the PSCC cube was damaged shortly after loading the plain, and generated a very long crack which almost penetrated the diagonal of the whole rectangular body. The crack developed top-down along the bearing face; the crack width became very wide when approaching the upper bearing, and was narrow closer to the lower bearing. In the MOSCC cube with a mixture of steel fibers, the cracks are narrow and developed slowly, thus the SCC cube could bear loads over a longer time. The elastic modulus drawn from the tests is listed in Table 8 below.

Table 8. Axial compressive stiffness test results.

Group No.	Compressive Strength of 1/3 Axial Core F_a (KN)	Initial Loading F_0 (KN)	Bearing Area of Specimen A (mm^2)	Last Reading of Strain Meter Δn ($\times 10^{-3}$ mm)	Average Value of Elastic Modulus E_c (MPa)
P-0	144.7	5.0	10,000	42.9	34,560
OS1	190.0	5.0	10,000	44.7	36,200
OS2	215.6	5.0	10,000	46.4	36,500
MS6	232.6	5.0	10,000	49.8	37,100
OS1 + MS6	222.0	5.0	10,000	57.0	38,070
OS2 + MS6	277.4	5.0	10,000	64.9	41,930

Figure 16 indicates that the axial compressive stiffness of steel fiber reinforced SCC increased with the increment of the addition of steel fibers. When the steel fiber addition amount was 1% OS, 2% OS, 6% MS, and 1% OS + 6% MS respectively the addition of steel fiber had little impact on the axial compressive stiffness, but with 2% OS + 6% MS the axial compressive stiffness has notable improvement compared with cases of other additions of steel fibers. This indicates that the addition of a mixture of two different kinds of steel fibers may result in some degree of improvement to axial compressive stiffness. However, the amount of steel fibers added has less impact on axial compressive stiffness in general.

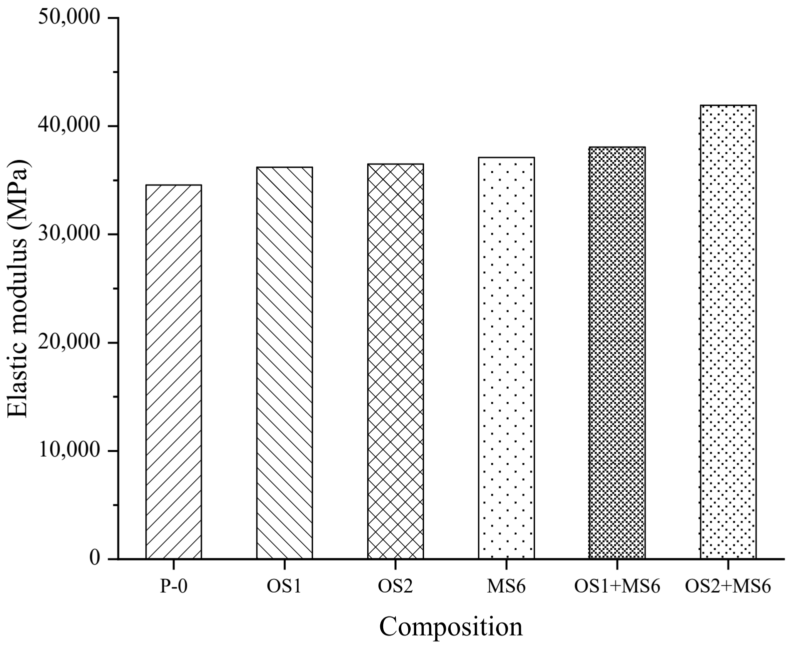


Figure 16. Axial compressive stiffness illustration.

3.5. Bending Toughness

The bending toughness loading defection curve of SCC fluctuated greatly with different volume fractions of steel fiber. The ultimate loads of a specimen increased with the increment of added fiber volume fraction, and the curve becomes fuller and presents greater toughness. The major results of the bending toughness test are shown in Table 9. Compared with PSCC, with the single addition of steel fiber, the compressive strength of SCC improved by 27.5%, 37.3% and 45.1% respectively and its equivalent bending toughness improved by 100%, 161.5% and 230.8%, while its bending toughness ratio improved 60.0%, 96.0% and 132.0% respectively when the volume addition of ordinary steel fiber was 1% and 2% and the volume addition of ultra-short and ultra-fine steel fiber was 6%. Compared with PSCC, the initial cracking strength of SCC improved by 60.8% and 119.6% respectively, and the equivalent bending toughness improved by 323.1% and 453.8% respectively, while the bending toughness ratio improved by 144.0% and 156.0% respectively, in the cases of a mixture of volume addition 1% ordinary steel fiber and 6% volume addition of ultra-short and ultra-fine steel fibers, and mixture of 2% ordinary steel fiber and 6% ultra-short and ultra-fine steel fiber. Hence it is clear that the bending toughness of SCC can be improved by adding steel fiber or a mixture of steel fiber, while SCC with a higher content of ultra-short and ultra-fine steel fiber with a mixture of steel fiber presents the greatest effect.

Table 9. Bending toughness test results.

Test Code	Initial Loading (KN)	Ultimate Load (KN)	Flexural Initial Strength (MPa)	Equivalent Flexural Strength (MPa)	Fexural Toughness Ratio
P-0	17.0	17.0	5.1	1.3	0.25
OS1	21.8	26.3	6.5	2.6	0.40
OS2	23.2	28.9	7.0	3.4	0.49
MS6	24.5	30.1	7.4	4.3	0.58
OS1 + MS6	27.2	32.7	8.2	5.5	0.61
OS2 + MS6	37.3	49.3	11.2	7.2	0.64

Figure 17 shows the data drawn from the three-point bending toughness test in the given study. It shows that a mixture of steel fibers can effectively improve the toughness of center displacement of material and prohibit the generation of micro-cracks in a flexural test. In Dimas [13] experiment in testing bending toughness, the average initial cracking strength was 3.69 MPa, and compound material C1.5% reached the highest tensile strength, and increased by 2.3 times that of UN-reinforced base material, while the effect of the mix is not so great. In a given test, the average initial cracking bend strength reached up to 7.57 MPa. Figure 17 shows that all the curves gradually decline after reaching their top. This is because before cracking, the steel fiber did not slip and move against SCC. Thus, in the loading displacement curve, a linear relation is formed and the skew rate is great. Afterwards, the curve presented many sections of curves, and the displacement at mid-span has a slow increase under the same loads. As the increment of addition increases to the whole base material, and the cohesion strength between the fiber and concrete base body is gradually reduced, which limits improvement to the compressive strength of the material.

The initial cracking strength, equivalent flexural strength, and bending toughness of the SCC specimen are proportional to the volume addition of steel fiber as shown in Figure 18. Pons et al. [27] and Gisele C.S. [5] got results that are compatible with those in this study, assessing that the toughness of the reference mixture was increased due to the addition of steel fibers. This proved that the bending toughness of concrete can be improved by incorporating a mixture of steel fibers. According to Abrishambaf et al. [28] and Thomas [29], this is the expected behavior once fibers are used to improve bending toughness.

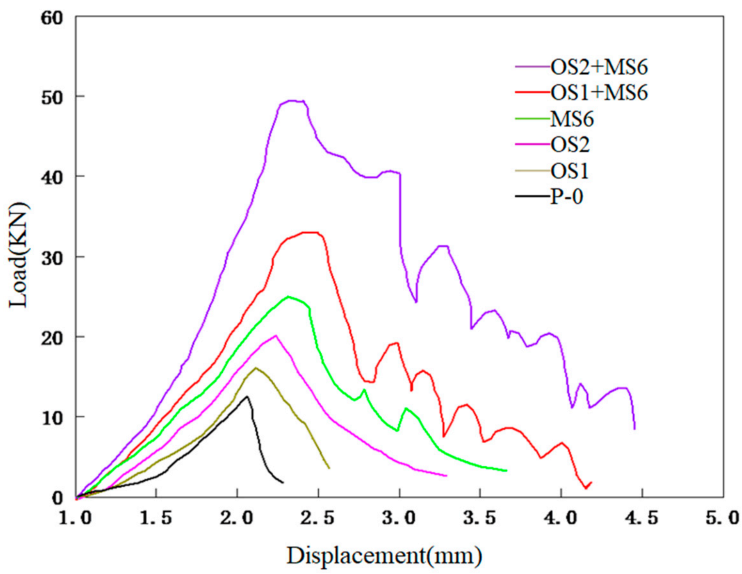


Figure 17. Load–displacement curve.

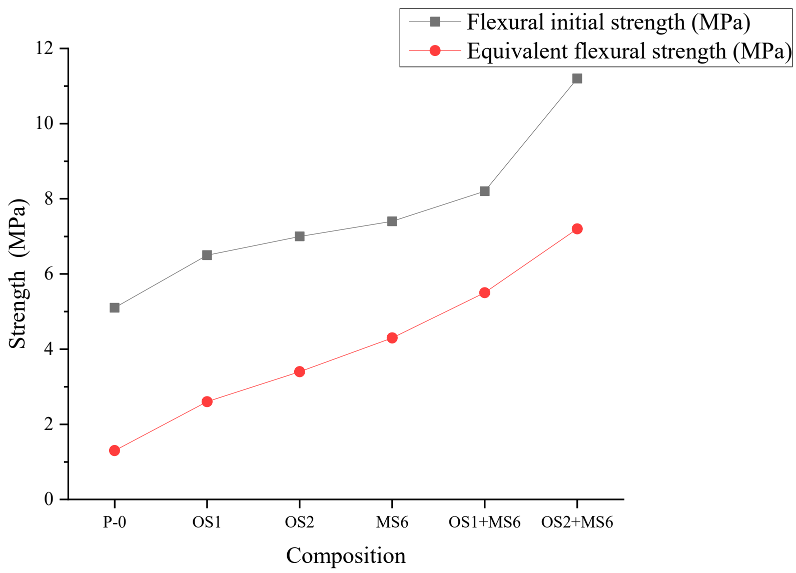


Figure 18. Bending toughness illustration.

4. Discussion

4.1. Addition Amount Recommendation

According to the cube's compressive strength, flexural strength, axial compressive strength, axial compressive stiffness, and bending toughness, it is clear that the addition of steel fiber can effectively improve the mechanical properties of steel fiber reinforced SCC, however, it is hard to determine which mix ratio can most improve the SCC. Therefore, by normalizing the data, the selected criteria should be shortened between 0 and 1 to find the optimal recommended mixing ratio, and by accumulating the specified criteria values, the combined effect of steel fibers on SCC can be determined.

The data normalization formula is shown as follows:

$$D_n = \frac{D - D_{min}}{D_{max} - D_{min}} \tag{9}$$

where D is the original value of test data, D_{max} is the maximum value of the test data, D_{min} is the minimum value of test data, D_n is the normalized value of test data.

The comprehensive influence of steel fiber on SCC is shown in Figure 19. It shows that the incorporation of steel fiber can greatly improve the mechanical property of SCC, and with the increase of the added amount of steel fiber the SCC property is improved constantly. Furthermore, the effect of the fiber mixture is greater. This is because the steel fibers are distributed in multiple directions inside the concrete. MS fibers can effectively prevent the expansion and extension of small cracks in the concrete, and OS fibers can inhibit the propagation of large cracks. The two are mixed and can give full play to their respective roles to prolong the test block cracking time, thereby increasing the energy absorbed by the SCC during failure, increasing its strain energy and relative toughness. Hence higher content of MOSCC can effectively prohibit the development of cracks in SCC and can improve the cracking resistance of SCC.

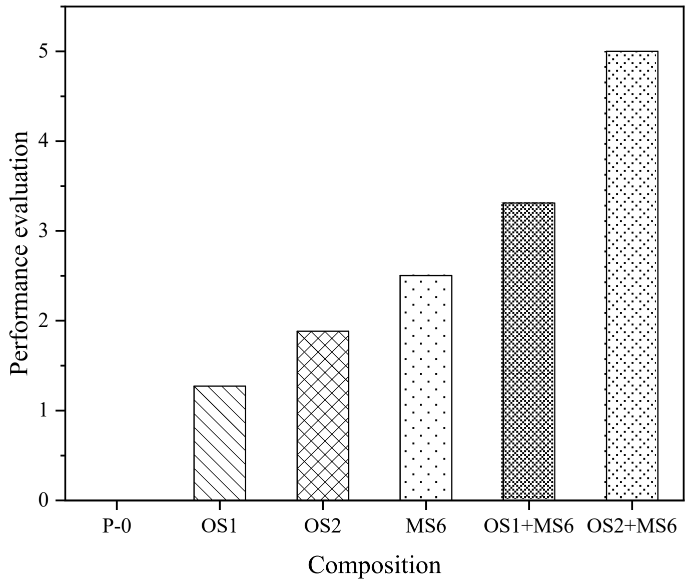


Figure 19. Comprehensive influence of fibers content on SCC.

4.2. Comparison

Burcu [11] applied three different typed steel fibers and incorporated them in two different volume fractions into the mixture, the cement used was ordinary Portland cement with a density of 3.17 g/cm^3, while the density of silica fume was 2.5 g/cm^3, the maximum particle size of aggregate was 16 mm. PSCC is plain self-consolidating concrete, MOSCC (C1.5H) is concrete with 1.0% high strength straight steel fiber (length of 6 mm and diameter of 0.15 mm) and 0.5% high strength hooked-end steel fiber (length of 30 mm and diameter of 0.55 mm). By obtaining the optimum addition and the above-mentioned optimum addition amount, the improvement rate of SCC properties is compared. The specific parameters are shown in Table 10. The table shows that with an increase in the addition of steel fiber, the vertical orientation of the fibers relative to the bending loading direction is more pronounced, thus improving the mechanical property of SCC. However, in Burcu's experiment, the added amount is insufficient to determine whether the optimum state of SCC is achieved, and the improvement mechanism of the steel fiber mixture is unclear. The test results in the experiment provided in this paper show clearly that a higher content of MOSCC improved the mechanical properties of SCC, and that the effect is pronounced. In this paper, considering the economic cost and practical problems, an excessive amount of steel fiber will affect the performance of concrete. The content of ultra-short and ultra-fine steel fibers is increased to 6%, which proves the feasibility of combining micro-steel fibers and ordinary steel fibers to enhance SCC. This test explained the mechanism of improving SCC by adding different amounts of steel fibers, and also verified that SCC containing a higher content of MOSCC not only achieved self-consolidation, which is hard to achieve with a higher steel fiber content, but also verified that compressive performance, rupture performance, axial compressive stiffness, and bending toughness improved constantly with the increasing addition of steel fibers, giving SCC a high cracking resistance capability. At the same time, we can apply the anti-cracking properties of MOSCC to bridge deck pavement.

Table 10. Comparison with Burcu's test.

Test	Burcu's Test			This Resarch		
	PSCC	MOSCC (C1.5H)	Improvement Rate	PSCC	MOSCC (OS2 + MS6)	Improvement Rate
Compressive test	115.3	123.6	7.2%	51.3	96.6	88.3%
Axial compressive stiffness	46.0	45.9	-	34.6	41.9	21.1%
Bending toughness	7.3	14.5	98.6%	5.1	11.2	119.6%

5. Conclusions

(1) MOSCC has a considerably improved strength and deforming property. In the case of volume addition of 2% ordinary steel fiber and volume addition of 6% ultra-short and ultra-fine steel fiber, when compared with PSCC, MOSCC has its 28 d cube compressive strength improved by 88.3%, and flexural strength improved by 261.0%.
(2) The MOSCC cube specimen demonstrated pronounced toughness in the loading process and showed cracking without rupture, while the loading-displacement curve showed a declining stage, and the region surrounded by curves and coordinate axles became fuller.
(3) MOSCC has a considerably improved toughness. In the case of the mixture of volume addition of 2% of ordinary steel fiber and 6% volume addition of ultra-short and ultra-fine steel fiber, compared with PSCC, the initial cracking strength of MOSCC improved by 119.6%, equivalent bending roughness improved by 453.8%, and bend toughness ratio improved by 156.0%.
(4) Damage conditions of MOSCC were changed. With a higher content of ultra-short and ultra-fine steel fiber mixture, the damage conditions of SCC can be improved. When MOSCC is damaged, its cracks will normally not penetrate throughout the whole specimen, as occurred to PSCC. The specimen generated ordinary cracks which caused no damage, and still had initial crack loading, and its damage shows a certain degree of ductility.

To sum up, it can be concluded that MOSCC achieved the workability of the mixture containing a higher content of admixture, and can greatly prevent the development of a concrete macro-crack, and thus it possesses excellent mechanical properties.

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