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Study on the relationship between the volume fraction of steel fiber and the increase of mechanical properties of concrete

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Abstract: *In order to study the effect of different volume rates of new steel fiber materials on the basic mechanical properties of ordinary concrete, cubic specimens with length, width and height of 100 mm were used for testing and comparison, and the volume admixture of steel fiber was selected as 0.5%, 1.0%, 1.5% and 2.0%, with 3 specimens per experimental group, totaling 90 specimens, and cubic specimens with length of 400 mm, width and height of 100 mm were used for flexural testing. The flexural test was carried out with rectangular specimens of 400 mm in length, 100 mm in width and 100 mm in height, 3 specimens per experimental group, 45 specimens in total. After the specimens were cured for 28 d, the mechanical properties were tested according to CECS13:2009 "Test Methods for Steel Fiber Concrete". The results showed that the mechanical properties of steel fiber concrete were significantly improved compared with those of ordinary concrete, with a maximum increase of 11.5% in compressive strength, 49.0% in flexural strength and 45.6% in splitting strength. This paper analyzes the relationship between the volume rate of steel fiber and the mechanical properties of concrete through the test results, and proposes the relationship curve equation of the effect of volume rate of steel fiber on the mechanical properties of concrete, which can be used as a reference for engineering design.*

Keywords: *Steel fiber volume rate; Incremental strength; Damage pattern; Fitting curve*

1. Introduction

Fiber reinforced concrete has good mechanical and physical properties, so it is widely used in various fields of civil engineering [1]. Compared with other fibers, steel fiber has the advantages of high tensile strength, crack resistance and good toughness. Therefore, steel fiber is also one of the most widely used fibers. A large number of scholars have carried out a lot of research on the influence of the steel fiber content and the length-diameter ratio on the mechanical properties of concrete, but the research on the relationship between the volume ratio of steel fiber and the increase of the mechanical properties of concrete is not deep enough.

In the aspect of adding new steel fiber material into concrete and analyzing its impact on the mechanical properties of concrete, the literature [2-7] has carried out experimental research on steel fiber concrete. The experimental results show that the mechanical properties of concrete can be better improved after adding appropriate amount of new steel fiber material, and the maximum improvement of bending and splitting resistance is achieved. The volume content and distribution form of steel fiber in concrete also have an impact on the performance of concrete. According to the research in literature [8-10], increasing the height of steel fiber concrete layer can increase the splitting tensile strength and flexural strength of composite steel fiber concrete. The upper steel fiber dimension of the test piece has little effect on improving the flexural strength of the test piece, and the greater the thickness of steel fiber dimension concrete (≤ 40% of the test piece height), the greater the flexural strength.

At present, there are many reports on the research results of the performance of steel fiber reinforced concrete, but the research on the relationship between the volume ratio of steel fiber and the mechanical properties of concrete is still insufficient to provide reference data for the practical application of engineering. In order to make the volume ratio of steel fiber more accurate in the corresponding project to meet the project requirements and reduce economic losses. Aiming at this problem, this paper has developed an experimental study on the influence of different steel fiber volume fraction on concrete performance. Through analyzing the increasing relationship between the

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volume fraction of steel fiber and the mechanical properties of concrete, the curve equation of the increasing relationship between the volume fraction of steel fiber and the mechanical properties of concrete has been established, which can be used as a reference for engineering design.

2. Trial

2.1 Test raw materials and mix ratio

According to the Specification for Design of Ordinary Concrete Mix Ratio (JGJ 55-2011) [11], the concrete with compressive strength of 40 MPa is designed. In this paper, P.O 42.5 ordinary Portland cement is selected; Medium sand; Crushed stone with particle size of 5-19 mm; Tap water in the laboratory; The water reduction rate of polycaroxylic acid superplasticizer (powder) ≥ 25%; The steel fiber is milled steel fiber produced by Hebei Heng hui Pu ang Steel Fiber Factory. The volume content of steel fiber is set at 0.5%, 1.0%, 1.5% and 2.0%. Because the volume fraction of steel fiber added is too large, it is easy to cause uneven dispersion of steel fiber, so the volume fraction of steel fiber is generally not more than 2.0% [11] , as shown in Table 1 and Table 2.

Table 1: Physical and mechanical properties of milled steel fibers

Fiber name	Average length/mm	Equivalent diameter/mm	draw ratio	Tensile strength/MPa
Milled steel fiber	41.4	0.58	71.0	≥800

Table 2: C40 grade concrete ratio design (Unit: kg.m3)

cement	Standard sand	spall	water	Water-reducing agent	Water-cement ratio
415	607	1233	195	0.4	0.47

2.2 Fabrication and curing of test pieces

Test pieces with length, width and height of 100 mm, 3 test pieces in each group, 90 test pieces in total; The test pieces with length of 400 mm, width and height of 100 mm, each group of 3 test pieces, a total of 45 test pieces. The following steps shall be taken to cast concrete test blocks on site , as shown in Figure 1.

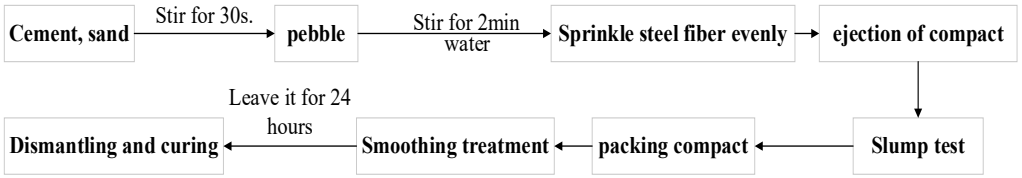

Figure 1: Flow chart of steel fiber concrete production

After the test piece is manufactured, it shall be placed indoors for 24 hours to remove the formwork, and then the test piece shall be placed in the standard curing room for curing. The test pieces of 3 days, 7 days and 28 days shall be tested according to CECS13: 2009 Test Method for Steel Fiber Reinforced Concrete, as shown in Figure 2.

Figure 2: Steel fiber concrete test block

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2.3 Loading and measuring device and loading

The test piece is loaded on the test equipment YAW-300 electro-hydraulic universal testing machine. The loading data is collected by the computer. See Figure 3 for specimen loading device. The loading process of the test piece adopts the loading speed control mode, the compressive loading speed is 0.5 MPa/s, the bending and splitting tensile loading speed is 0.05 MPa/s, and the test piece is continuously loaded until the failure.

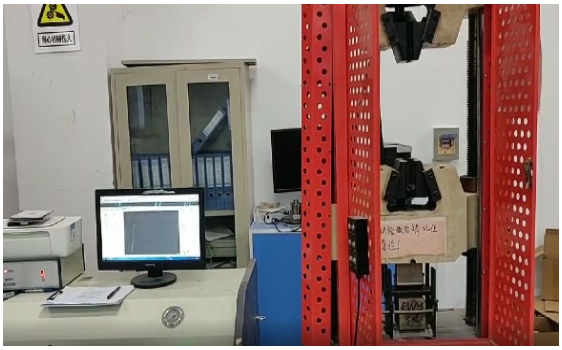

Figure 3: Universal testing machine

3. Test results and analysis

3.1 Cube compressive failure form

When the concrete is crushed and dropped on the side perpendicular to the compression surface after compression, the steel fiber hinders the expansion of the crack when the concrete is compressed, and part of the energy is released in the form of polymorphous cracks, showing the phenomenon of cracking but not breaking. This is because the steel fiber is distributed in the matrix concrete in the form of three-dimensional distribution in the whole concrete, which makes the damage pattern of the concrete better improved. See Figure 4 for the failure mode of the test piece.

(a) Ordinary concrete under compression *(b) Steel fiber reinforced concrete under compression*

Figure 4: Schematic diagram of the damage pattern of plain concrete and milled steel fiber concrete specimens under compression

3.2 Splitting tensile failure mode

Ordinary concrete is subject to splitting tension. When the load is loaded to the test piece, the crack will spread rapidly. When it is damaged, it will make a "bang" sound. The damage is sudden, and the crack develops single, with obvious brittle damage characteristics; Steel fiber reinforced concrete is subjected to splitting tension, and cracks appear when the load is loaded to the test piece. The cracks will develop more and more slowly. The steel fiber hinders the development of cracks after the matrix is damaged, and part of the energy is released by other cracks. In the process of crack expansion, the steel fiber also receives a part of the load, and still does not break, part of the steel fiber is pulled out of the matrix, and part of the steel fiber is still connected to the concrete test block, the concrete is not split in two, showing good ductility. The failure mode of the test piece is shown in Figure 5.

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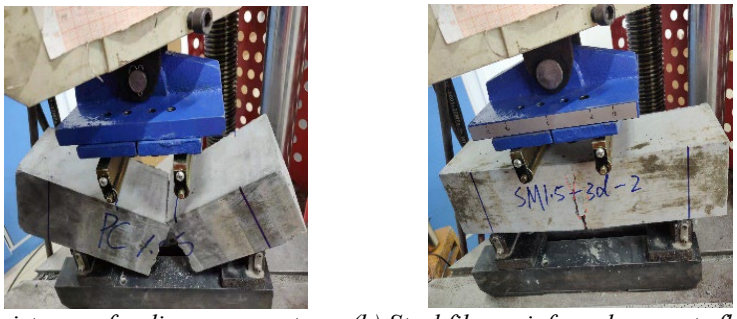
(a) Ordinary concrete splitting *(b) Steel fiber concrete splitting*

Figure 5: Schematic diagram of splitting and tensile damage patterns of plain concrete and milled steel fiber concrete specimens

3.3 Bending failure form

When cracks appear in the pressure concentration area during the loading process of ordinary concrete, the cracks develop rapidly, and the specimen is folded into two parts when it is damaged, accompanied by a loud noise. During the loading process of steel fiber reinforced concrete, when cracks appear in the pressure concentration area, during the crack propagation stage, the steel fiber hinders the crack propagation. After the failure, because some steel fibers are not pulled out, they are not folded into two halves. The cracks are winding and show good ductility. The failure mode of the test piece is shown in Figure 6.



(a) Bending resistance of ordinary concrete *(b) Steel fiber reinforced concrete flexural strength*

Figure 6: Schematic diagram of flexural damage morphology of plain concrete and milled steel fiber concrete specimens

Table 3: Mechanical properties of milled steel fiber concrete matrix

number	Compressive strength/MPa	A%	Bending strength/MPa	B%	Splitting tensile strength/MPa	C%
PC	41.64	-	4.06	-	5.24	-
SFRC 0.5	44.76	7.5	4.52	11.3	5.75	9.7
SFRC 1.0	45.33	8.9	5.05	24.4	6.41	22.3
SFRC 1.5	46.42	11.5	5.73	41.1	7.24	38.2
SFRC 2.0	45.27	8.7	6.05	49.0	7.63	45.6

Note: PC - plain concrete; SFRC 05 - concrete with 0.5% steel fiber content; SFRC10, SFRC15 and SFRC20 are the same; A%, B% and C% represent the increase of compressive, flexural and splitting tensile strength respectively.

3.4 Analysis of experimental results

The mechanical properties of milled steel fiber concrete are shown in Table 3. The addition of new steel fiber materials has significantly improved the mechanical properties of concrete. It can be seen from Figure 7 that the increase of compressive strength peaks when the volume ratio of steel fiber is 1.5%, and the maximum increase is 11.5% compared with the compressive strength of ordinary concrete. When the volume ratio of steel fiber exceeds 1.5%, the increase of compressive strength decreases, because the steel fiber content is too large to be evenly dispersed in the concrete. Before the volume fraction of steel fiber increased to 1.5%, the increase rate of flexural strength and splitting

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tensile strength has been accelerating; After the volume ratio of steel fiber is 1.5%, the increase of flexural strength and splitting tensile strength slows down several times. When the volume ratio of steel fiber is 2%, the flexural strength and splitting tensile strength of steel fiber concrete are increased by 49.0% and 45.6% respectively compared with ordinary concrete.

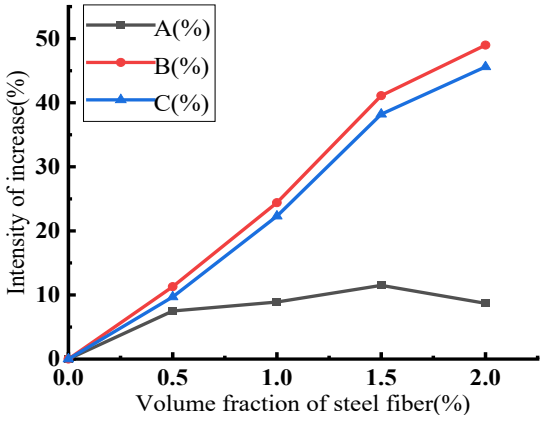

Figure 7: Relationship between volume rate of steel fiber and increase in compressive, splitting and flexural strengths

According to Figure 7, polynomial fitting is carried out respectively, and the fitting results are as follows:

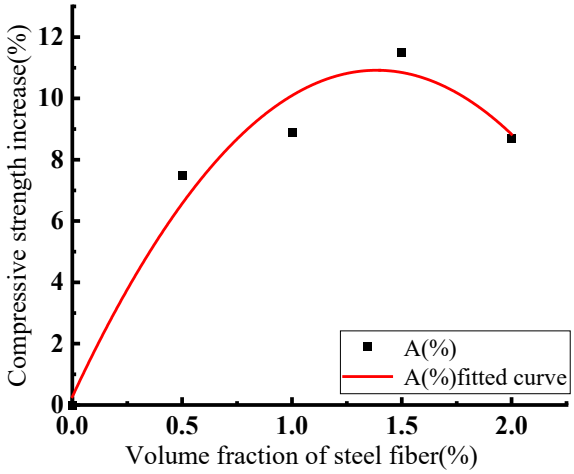

Figure 8: Fitted curve of steel fiber volume rate versus compressive strength increase

$$A\% = -55429V^2 + 1536.6V + 0.2686 \quad (1)$$

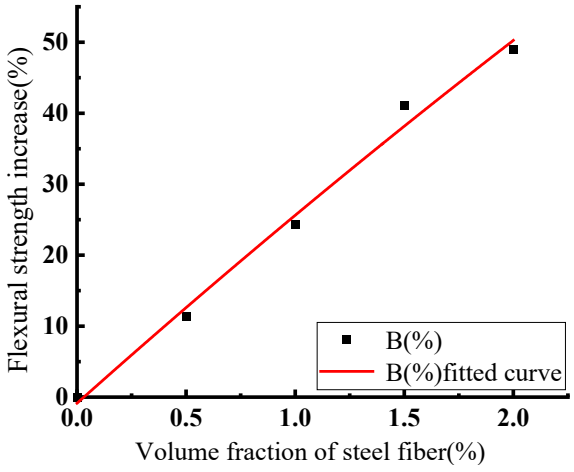

Figure 9: Fitted curve of steel fiber volume rate versus flexural strength increase

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$$B\% = -9142.9V^2 + 2738.9V - 0.8571 \quad (2)$$

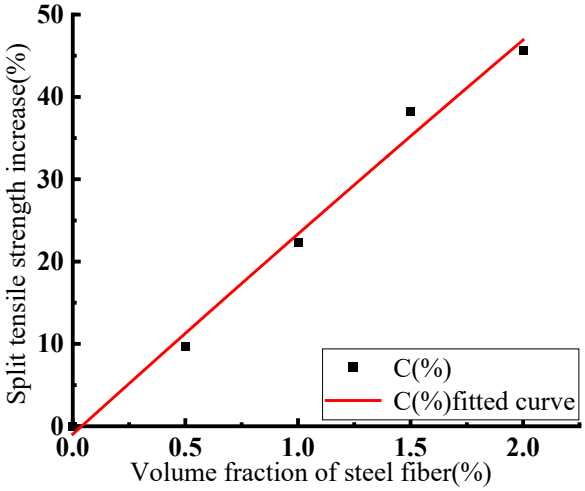

Figure 10: Fitted curve of steel fiber volume rate versus increase in splitting and tensile strength

$$C\% = -3714.3V^2 + 2468.3V - 0.9657 \quad (3)$$

Polynomial fitting of concrete compressive, flexural and splitting tensile test data with different steel fiber volume ratios is carried out by using Origin software, and the formulas (1), (2) and (3) are obtained, where, respectively represent the increase of compressive, flexural and splitting tensile strength, and represent the volume ratio of steel fiber, as shown in Figure 8, Figure 9 and Figure 10.

4. Conclusion

By adding new steel fiber materials into concrete and setting different volume ratio to carry out the test, the test data and the failure mode of the specimen under load are analyzed and studied, and the following conclusions are obtained.

1) After adding new steel fiber materials, the mechanical properties of ordinary concrete have been significantly improved, the maximum compressive strength has increased by 11.5%, the bending strength and splitting tensile strength have increased by 49.0% and 45.6% respectively.

2) The failure mode of concrete mixed with new steel fiber materials has been greatly improved, and the brittle failure characteristics of ordinary concrete have been changed. The concrete has reached the failure state of cracking but not breaking under compression, and cracking and continuous under splitting and bending tension, which ensures the integrity of the test piece and has a certain ductility.

3) Based on the analysis of the test results of steel fiber reinforced concrete, the relationship between the volume ratio of steel fiber and the increase of compressive strength, flexural strength and splitting tensile strength of concrete is established, which can provide reference for the engineering application of steel fiber reinforced concrete.

4) In this paper, the influence of volume fraction on the compressive, flexural and splitting tensile properties of concrete is studied. On the basis of this study, the relationship between the volume fraction of steel fiber, durability and impact resistance will be further studied.

References

[1] Brandt A M. Fiber reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering [J]. Composite Structures, 2008, 86(1): 3-9.
[2] Guo Z. Experimental Study on the Effect of Volume Ratio of Steel Fiber on Mechanical Properties of Ceramsite Concrete [J]. Open Access Library Journal, 2022.
[3] Niu Long, Zhang Shiping, Wei Youxin. Effect of steel fiber admixture on the mechanical properties of concrete [J]. Concrete and Cement Products, 2019(03): 51-54.
[4] Yang Meng, Huang Chengkui. Study on stress strain curve of high strength steel fiber reinforced concrete under uniaxial tension [J]. China Civil Engineering Journal, 2006, 39(3): 55-61.

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[5] Han Rong, Zhao Shunbo, Qu Fulai. Experimental study on the tensile performance of steel fiber reinforced concrete [J]. China Civil Engineering Journal, 2006, 39(11): 63-67.
[6] Hao Yifei, Hao Hong. Test analysis on spiral steel fiber reinforced concrete subjected to impact loads [J]. Journal of Tianjin University (Science and Technology), 2016, 49(4): 355-360.
[7] Yang Yong, Ren Qingwen. Experimental study on the mechanical properties of steel fiber concrete [J]. Journal of Riverhead University (Natural Science Edition), 2006, 34(1): 92 94.
[8] Zou Yansheng. Study on the effect of dosing and layered placement on the mechanical properties of steel fiber concrete [J]. Hunan Transportation Science and Technology, 2021, 47(01): 52-55.
[9] Peng Ao, Jiao Chujie. Research on mechanical properties and damage characteristics of composite steel fiber reinforced concrete and layered steel fiber reinforced concrete [J]. Concrete, 2020(08): 67-71+78.
[10] Zhou Rong, Liu Tao, Zhang Zhimei. Experiment Study on Compression Behavior of Steel Fiber Reinforced Concrete [J]. Structural Engineer, 2007(01): 82-85.
[11] JGJ 55—2011 Specification for mix proportion design of ordinary concrete[S]. Beijing: China Architecture&Building Press, 2011.