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Research Article

Mechanical Properties of Steel Fiber-Reinforced Concrete by Vibratory Mixing Technology

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As a kind of important engineering material, steel fiber-reinforced concrete was used widely in civil engineering. Up to now, steel fiber-reinforced concrete was usually produced by the traditional mixing method. For the reason of uniform distribution of fiber, the reinforcement of mechanical properties of concrete was inadequately performed. In this paper, C50 steel fiber-reinforced concrete and C60 steel fiber-reinforced concrete were manufactured by traditional mixing and vibratory mixing methods, respectively, and then, the cube compression test, flexural test, splitting tensile test, and the bending test were carried out. The reinforcement effects of mechanical properties were analyzed by comparing the traditional mixing and vibratory mixing methods. The results show that vibratory mixing can effectively improve the distribution of steel fibers in concrete and can increase the density of steel fiber concrete, and therefore, it effectively improves the mechanical properties of steel fiber-reinforced concrete when compared to the traditional mixing method.

1. Introduction

As an important building material, concrete has been widely used in civil engineering applications such as bridges and roads engineering, and the related experimental study of the mechanical properties of concrete was also fruitful [1–5]. With the vigorous development of engineering construction, high-performance concretes such as fiber-reinforced concrete was applied gradually in important engineering structures [6–10]. Among these high-performance concretes, for the advantages of low cost, easy fabrication, and performance improvements, obviously, steel fiber-reinforced concrete was used widely in the current engineering field [9, 10]. However, the study showed that uneven incorporation of steel fiber would affect the fluidity and uniformity of concrete mixing and even result in fiber bonding, which eventually affects the reinforcement effect of mechanical properties [11–15]. Up to now, most research paid attention on the improvement effect of different types of fiber or optimum fiber content, but little literature paid attention on the difference of improvement effect by various stirring technologies. As a kind of new stirring technology, compared to traditional stirring technology, vibratory mixing technology could effectively improve the distribution of fibers in concrete, further increase the density of steel fiber concrete, and finally improve the mechanical properties of steel fiber-reinforced concrete [16–20]. But, at present, vibratory mixing technology has not been widely used in engineering, and research on its improvement of concrete mechanical properties is inadequate at home and abroad. For such reasons, in this paper, different steel fiber incorporation volume concrete test specimens of various mix proportions were prepared, which were made by different stirring technologies. And then, compression test, flexural test, splitting tensile test, and bending test were conducted; finally, the differences of workability and mechanical properties of steel fiber concrete made by vibratory

Table 1: Test mix of steel fiber concrete.

Specimen number	Steel fiber parameter (%)	Steel fiber (kg)	Water (kg)	Cement (kg)	Coarse aggregate (kg)	Fine aggregate (kg)	Additive (kg)	Sand-coarse aggregate ratio
C50	0	0	172	347.5	1181.3	664.5	2.7	0.36
	0.5	39	172	347.5	1159.5	674.3	2.7	0.36
	1	58.9	172	347.5	1148.6	679.2	2.7	0.36
	1.5	78.5	172	347.5	1137.8	684.9	2.7	0.36
	2	117	172	347.5	1115.1	693.7	2.7	0.36
C60	0	0	164	451.8	1078.2	660.8	4.9	0.36
	0.5	39.3	164	451.8	1055.8	671.2	4.9	0.36
	1	78.5	164	451.8	1033.5	681.5	4.9	0.36
	1.5	117.8	164	451.8	1011.1	691.9	4.9	0.36
	2	157	164	451.8	988.8	702.2	4.9	0.36

mixing and the traditional mixing technologies, respectively, were compared and analyzed.

2. Materials and Test Programs

2.1. Materials

2.1.1. Steel Fiber. The physicochemical parameter of steel fiber should meet the requirements of JGT 472-2015. The length of steel fiber should be 20 mm~60 mm and diameter or equivalent diameter should be 0.3 mm~1.2 mm; length to diameter ratio was 30~65.

2.1.2. Cement. P.O 42.5 ordinary Portland cement was used in this paper, and each performance index of cement and its strength of 3 days and 28 days were checked according to the performance index of "General Portland Cement" (GB175-2007).

2.1.3. Fine Aggregate. Good quality graded sand was selected, and fineness modulus should be controlled in 2.3 to 3.0; fine aggregate performance was checked according to GB14684-2011.

2.1.4. Coarse Aggregate. Test selection of hard texture, graded continuous gravel, and aggregate shape with a more uniform edge polyhedron was made as well, with a particle size of 5 mm~20 mm and clay content <1%. The "standard test method for building pebbles, gravel" (GB/T14685-2011) was used as test performance indicators of the coarse aggregate.

2.1.5. Admixture. Polycarboxylate superplasticizer was used as admixture, with water reduction rate not less than 25%. The amount of admixture was 0.5%~1% of cement content.

2.1.6. Mineral Admixture. Addition of fly ash should be consistent with the provisions of GB/T1596.

2.2. Mixture Proportion Design. The purpose of this experiment is to study the improvement of mechanical properties of different types of steel fiber-reinforced concrete (SFRC) which was made by ordinary stirring and vibratory mixing, respectively. In the field of engineering, steel fiber-reinforced concrete was always used as high-strength concrete, so in this paper, two kinds of high-strength concrete C50 and C60 were studied in this paper, and the amounts of steel fiber admixture were 0.5%, 1%, 1.5%, and 2%, respectively. The specific mix is shown in Table 1.

2.3. Sample Preparation. To ensure uniform distribution of basalt fibers in the mix, sand and macadam were mixed firstly, and then, cement and fiber were added. After the mixtures were mixed for 30 seconds, the water and additives were added during the course of stirring. The stirring time of steel fiber-reinforced concrete was 3 minutes; and the mixing process is shown in Figure 1.

The prepared mixture was put into the test mold to vibrate, and then, it was made flat. The mold was removed after 48 hours maintenance, and then specimens were cured in the standard curing room at the temperature of 20°C and relative humidity of 97%. The curing process is shown in Figure 2.

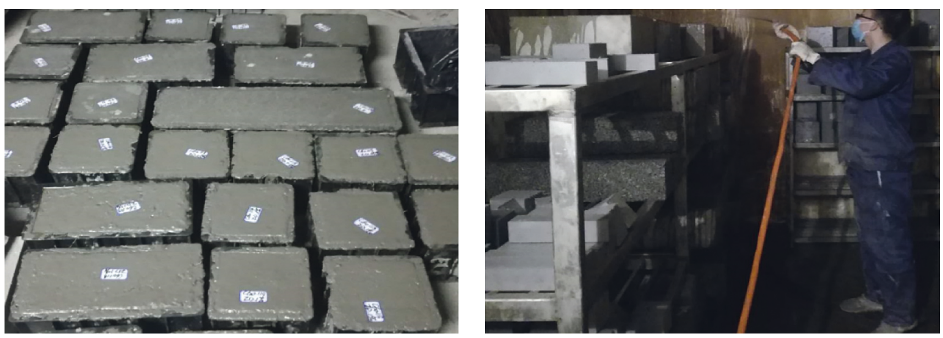
The strengthening mechanism of vibration was to make cement powder and fine material to quickly disperse; water and cement hydration reaction speed was expedited evenly so that the microscopic structure of the cement concrete was improved, and the dosage of cement was effectively reduced. The contrast of effect between vibratory mixing and traditional mixing is shown in Figure 3, and the contrast of microstructure between vibratory mixing and traditional mixing is shown in Figure 4.

3. Experimental Programs

3.1. Cube Compression of Steel Fiber-Reinforced Concrete. The standard length of 150 mm cube specimen was used in the cube compressive strength test, and the methods and procedures of "ordinary concrete mechanical properties test method standard" GB/T 50080-2016 and "test method for fiber concrete" (CECS 13-2009) were referred to conduct the test. The constant-speed stress control was used in this test, and loading speed was 0.6 MPa/s; the specimen would be automatically unloaded, and the strength of damage was

(a) (b)

Figure 1: Mixing process of steel fiber concrete by vibratory mixing.



(a) (b)

Figure 2: The manufacturing and curing operation of specimens.

Cement and water molecular cluster

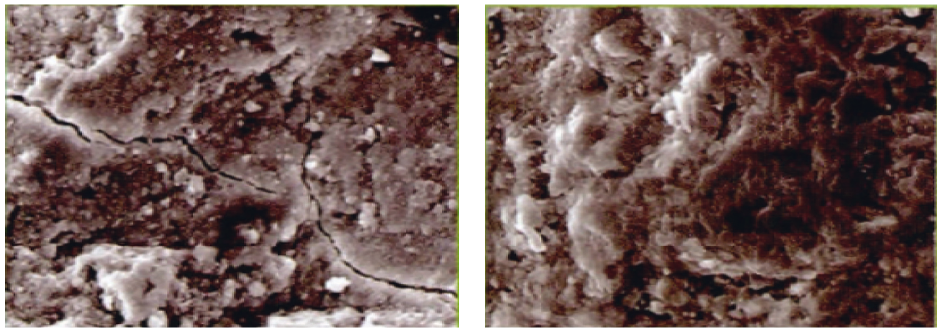
Diffusion of cement and water molecular cluster

Figure 3: Contrast of effect between vibratory mixing and traditional mixing.

recorded by the machine. The cube compressive strength testing machine is shown in Figure 5.

3.2. Flexural Test of Steel Fiber-Reinforced Concrete. The existing literatures showed that the flexural tests of steel fiber-reinforced concrete made by vibratory mixing were very limited up to now. For this purpose, a series of beam specimens (at the age of 28 d) with the size of 100 mm × 100 mm × 400 mm were used to study the flexural strength in this study. The three-point loading tests were carried out using the flexural testing machine (NYL-300C type) in accordance with the Chinese standard (JTG E30-2005). The test apparatus of the flexural strength test is presented in Figure 6.

3.3. Split Tensile Test of Steel Fiber-Reinforced Concrete. The standard length of 150 mm cube specimen was used in the splitting tensile strength test, and each group includes 3 specimens. The 3000 kN pressure testing machine was used in this test, and the splitting position should be drawn before the splitting test, as shown in Figure 7.



(a) (b)

Figure 4: Contrast of microstructure between (a) traditional mixing and (b) vibratory mixing.

(a) (b)

Figure 5: Cube compressive strength testing machine.

4. Result and Discussion

4.1. Cube Compressive Strength of Steel Fiber Concrete

4.1.1. Cube Compressive Strength of Steel Fiber Concrete Made by Traditional Stirring. It can be seen from Figure 8(a) that, for the traditional mixing method, the compressive strength of steel fiber-reinforced concrete CF50 increases as the steel fiber content increases. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete compressive strength increases by 7.05%, 13.79%, 18.17%, and 20.85%. Figure 8(a) shows that while fiber content is less than 1%, the compressive strength increasing rate is faster; as the fiber content is more than 1% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

Figure 8(b) details that, similar to CF50, the compressive strength of steel fiber-reinforced concrete CF60 also improves with the increase of steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete compressive strength increases by 6.33%, 20.59%, 24.57%, and 26.35%. Figure 8(b) also shows that while fiber content is less than 1%, the compressive strength increasing rate is faster; as the fiber content is more than 1% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

Comparing CF50 to CF60, it can be found that fiber-reinforced effect of compressive strength of high-strength concrete CF60 is higher than that of CF50; for example, at the same fiber content of 1%, the compressive strength increases by 20.59% in CF60; in CF50, the value is 13.79%. In other words, for vibratory mixing, steel fiber enhanced effect of high-strength concrete is more obvious.

4.1.2. Cube Compressive Strength of Steel Fiber Concrete Made by Vibratory Mixing. Figure 9(a) shows that, for the vibratory mixing mode, with the increase of the steel fiber content, the cubic compressive strength of concrete CF50 increases continuously. At the fiber content of 0.5%, 0.75%, 1%, 1.5%, and 2%, the concrete compressive strength increases by 10.23%, 11.35%, 12.12%, 13.79%, and 17.71%. Figure 9(a) shows that while fiber content is less than 0.5%, the compressive strength increasing rate is faster; as the fiber content is more than 0.5% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

(a) (b)

Figure 6: Flexural tensile strength test apparatus.

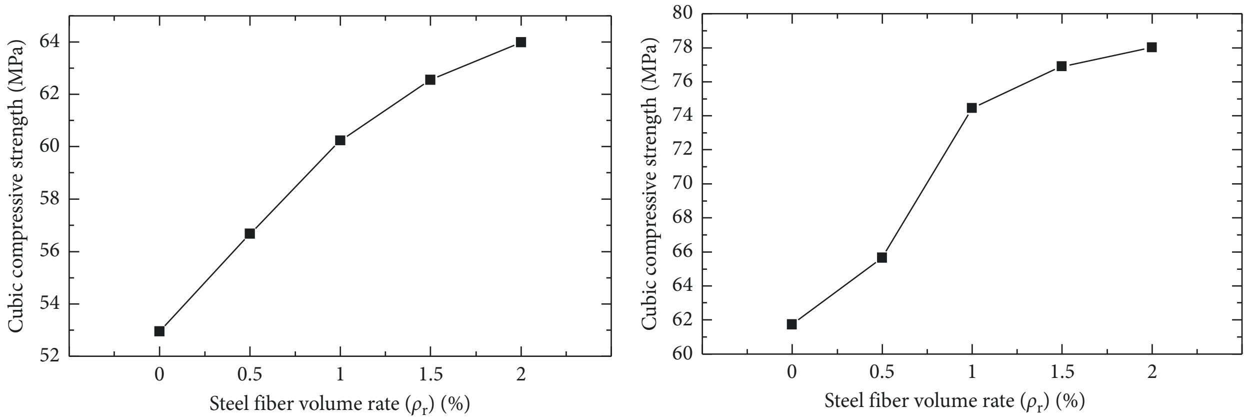
(a) (b)

Figure 7: Cube splitting tensile strength testing equipment.

Figure 9(b) shows that, similar to CF50, the compressive strength of CF60 also improves with the increase of steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete compressive strength increases by 7.9%, 14.14%, 19.96%, and 22.89%. Figure 9(b) also shows that while fiber content is less than 1%, the compressive strength increasing rate is faster; as the fiber content is more than 1% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

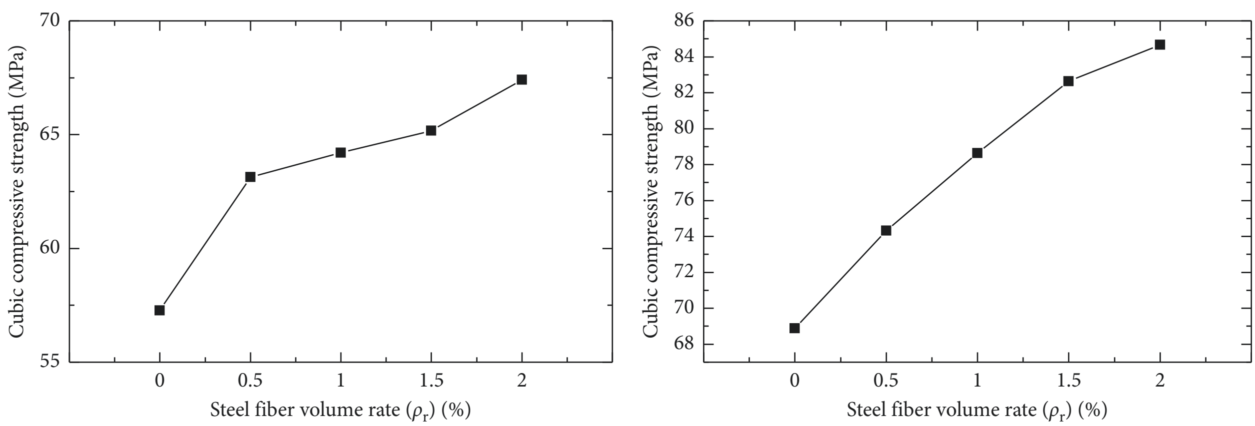
Comparing CF50 to CF60, it can be found that fiber-reinforced effect of compressive strength of high-strength concrete CF60 is higher than that of CF50; for example, at the same fiber content of 1.5%, the compressive strength increases by 19.96% in CF60; in CF50, the value is 13.79%. In other words, for vibratory mixing, steel fiber enhanced effect of high-strength concrete is more obvious.

4.1.3. Effect of Different Mixing Methods on the Compressive Properties of Concrete. It can be seen from Figure 10(a) that, with the increase of the steel fiber content, the cubic compressive strength of CF50 concrete increases continuously. Comparing to traditional mixing concrete, with the same steel fiber content, the concrete made by vibratory mixing is equipped with higher compressive strength. At the fiber content of 0%, 0.5%, 0.75%, 1%, 1.5%, and 2%,



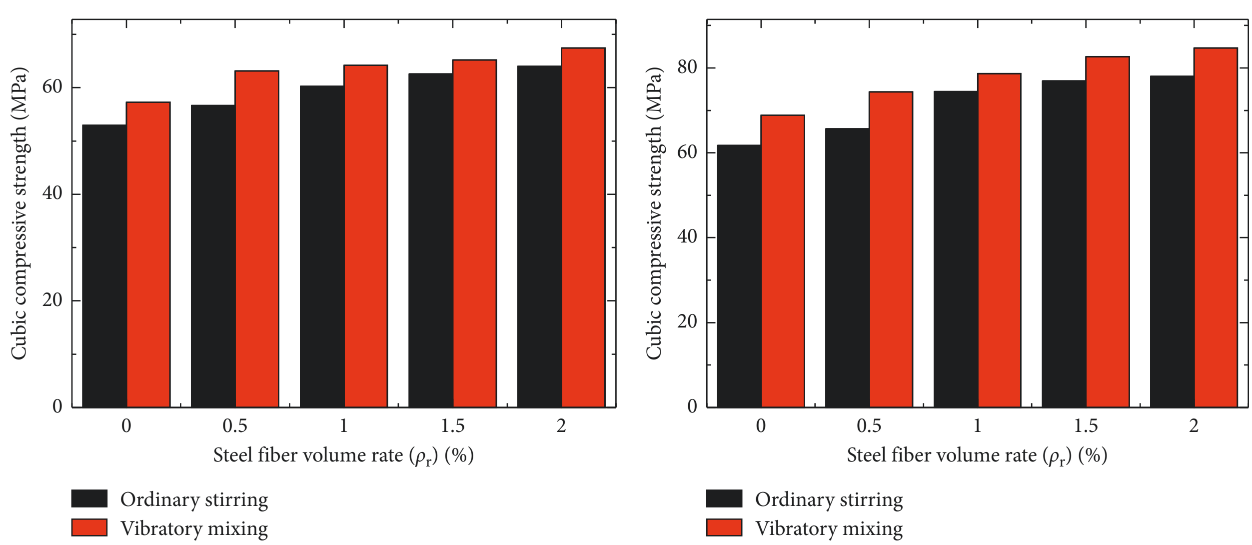
(a) (b)

Figure 8: Relationship between compressive strength and steel fiber content. (a) CF50; (b) CF60.



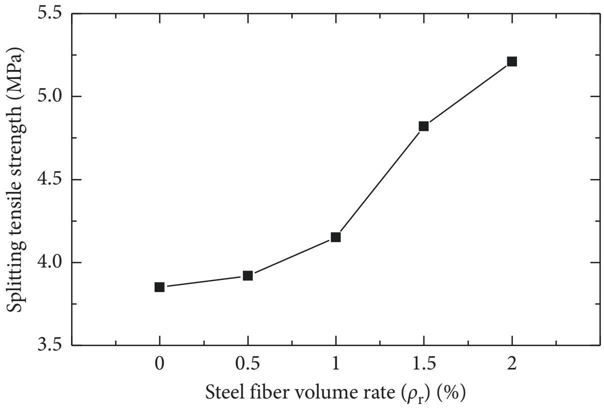
(a) (b)

Figure 9: Relationship between cube compressive strength and steel fiber content. (a) CF50; (b) CF60.



(a) (b)

Figure 10: Effect of the mixing method on cube compressive strength of concrete. (a) CF50; (b) CF60.



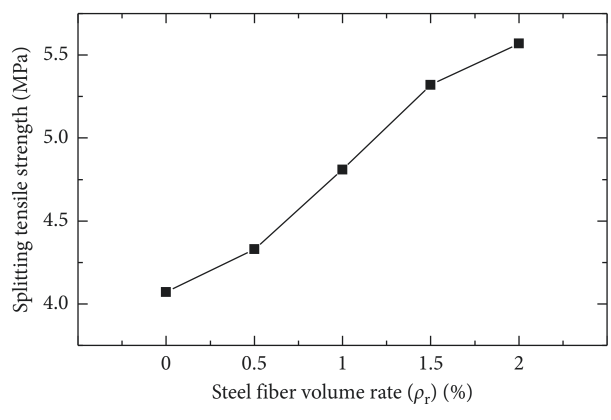


Figure 11: Relationship between splitting tensile strength and steel fiber content. (a) CF50; (b) CF60.

comparing to traditional mixing concrete, the compressive strength of vibratory mixing concrete increases by 8.18%, 11.40%, 8.80%, 6.59%, 4.17%, and 5.36%. Figure 10(a) also shows that while fiber content is less than 0.5%, the compressive strength improvement is faster; for example, at 0.5% fiber content, the compressive strength of vibratory mixing concrete increased by 11.4%; as the fiber content is more than 0.5% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

Figure 10(b) shows that, with the increase of the steel fiber content, the cubic compressive strength of CF60 concrete increases continuously. Comparing to traditional mixing concrete, at the same steel fiber content, the concrete made by vibratory mixing is equipped with higher compressive strength. At the fiber content of 0%, 0.5%, 1%, 1.5%, and 2.0%, comparing to traditional mixing concrete, the compressive strength of vibratory mixing concrete increases by 11.58%, 13.22%, 5.61%, 7.54%, and 8.53%. Figure 10(b) also shows that while fiber content is less than 0.5%, the compressive strength improvement is faster, for example, at 0.5% fiber content, the compressive strength of vibratory mixing concrete increased by 13.22%; as the fiber content is more than 0.5% (e.g., 1.5% and 2%), the compressive strength increasing rate becomes slow.

Comparing CF50 to CF60, it can be found that fiber-reinforced effect of compressive strength of high-strength concrete CF60 is higher than that of CF50; for example, at the same fiber content of 0.5%, the compressive strength increases by 13.22% and 11.40% in CF60 and CF50, respectively.

4.2. Splitting Tensile Strength of Steel Fiber Concrete

4.2.1. Splitting Tensile Strength of Steel Fiber Concrete Made by Tradition Mixing. It can be seen from Figure 11(a) that, for the traditional mixing method, the splitting tensile strength of steel fiber-reinforced concrete CF50 increases as the steel fiber content increases. At the fiber content of 0.5%, 0.75%, 1%, 1.5%, and 2%, the concrete splitting tensile strength increases by 1.82%, 6.22%, 7.79%, 25.26%, and 35.41%. Figure 11(a) shows that while the fiber content is less than 1%, the splitting tensile strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

Figure 11(b) details that, similar to CF50, the splitting tensile strength of steel fiber-reinforced concrete CF60 also improves with the increase in steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete splitting tensile strength increases by 6.39%, 18.18%, 30.71%, and 36.86%. Figure 11(b) also shows that while the fiber content is less than 1%, the splitting tensile strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

Comparing CF50 to CF60, it can be found that, at the same fiber content, fiber reinforcement effect of splitting tensile strength of high-strength concrete CF60 is higher than that of CF50; for example, at the fiber content of 1%, the splitting tensile strength increases by 18.18% and 7.79% in CF60 and CF50, respectively. In other words, for traditional stirring, steel fiber enhanced effect of high-strength concrete is more obvious.

4.2.2. Effect of Steel Fiber Content on Splitting Tensile Strength of Concrete under Vibratory Mixing. It can be seen from Figure 12(a) that, for the traditional mixing method, the splitting tensile strength of steel fiber-reinforced concrete CF50 improves as the steel fiber content increases. At the fiber content of 0.5%, 0.75%, 1.0%, 1.5%, and 2.0%, the concrete splitting tensile strength increases by 4.44%, 7.96%, 11.99%, 28.57%, and 36.99%. Figure 12(b) also shows that while the fiber content is less than 1%, the compressive strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

Figure 12(b) shows that, similar to CF50, the splitting tensile strength of steel fiber-reinforced concrete CF60 also improves with the increase obviously in steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete splitting tensile strength increases by 12.11%, 28.74%, 43.23%, and 66.75%.

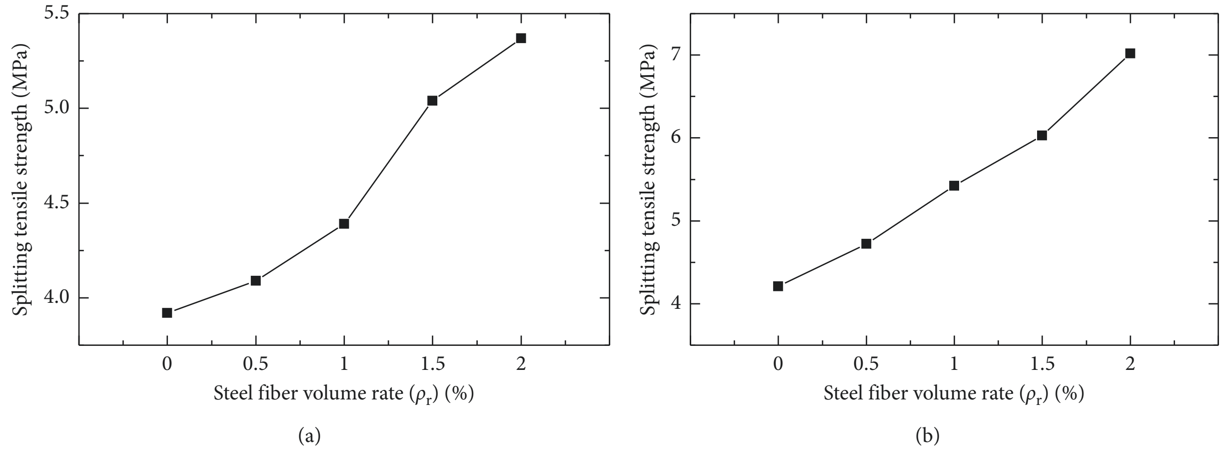


Figure 12: Relationship between splitting tensile strength and steel fiber content. (a) CF50; (b) CF60.

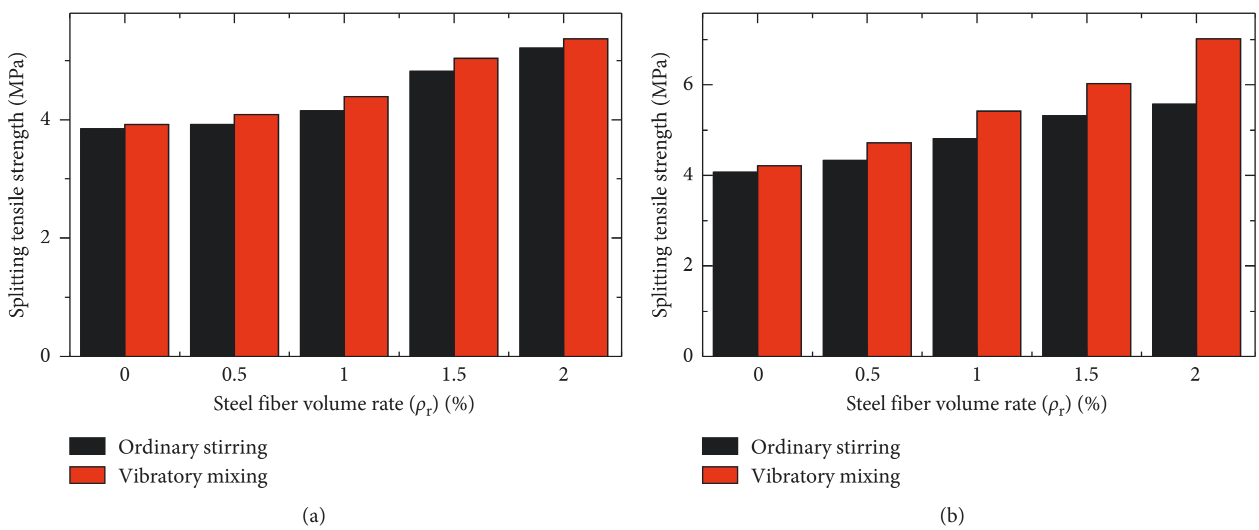


Figure 13: Effect of different mixing methods on the splitting tensile properties of steel fiber concrete. (a) CF50; (b) CF60.

Comparing CF50 to CF60, it can be found that, at the same fiber content, fiber reinforcement effect of splitting tensile strength of high-strength concrete CF60 is higher than that of CF50; for example, at the fiber content of 1%, the splitting tensile strength increases by 28.74% and 11.99% in CF60 and CF50, respectively. In other words, for vibratory mixing, steel fiber enhanced effect of high-strength concrete is more obvious.

4.2.3. Effect of Different Mixing Methods on the Splitting Tensile Properties of Steel Fiber Concrete. It can be seen from Figure 13(a) that, with the increase of the steel fiber content, the splitting tensile strength of CF50 concrete improves continuously. Comparing to traditional mixing concrete, at the same steel fiber content, the concrete made by vibratory mixing is equipped with higher compressive strength. At the fiber content of 0%, 0.5%, 0.75%, 1%, 1.5%, and 2%, comparing to traditional mixing concrete, the splitting tensile of vibratory mixing concrete increases by 1.82%, 4.44%, 3.48%, 5.78%, 4.51%, and 3.01%. Figure 13(a) also shows that, at the fiber content of 1.0%, comparing to traditional mixing, the splitting tensile strength of concrete made by vibratory mixing improves obviously.

Figure 13(b) shows that, similar to CF50, with the increase of the steel fiber content, the splitting tensile strength of CF60 concrete improves continuously. Comparing to traditional mixing concrete, at the same steel fiber content, the concrete made by vibratory mixing is equipped with higher splitting tensile strength. At the fiber content of 0%, 0.5%, 1%, 1.5%, and 2.0%, comparing to traditional mixing concrete, the splitting tensile strength of vibratory mixing concrete increases by 3.44%, 9.01%, 12.68%, 13.35%, and 26.03%. Figure 13(b) also shows that, at the fiber content of 2.0%, comparing to traditional mixing, the splitting tensile strength of concrete made by vibratory mixing improves obviously.

Comparing CF50 to CF60, it can be found that fiber-reinforced effect of splitting tensile strength of high-strength concrete CF60 is higher than that of CF50; for example, at

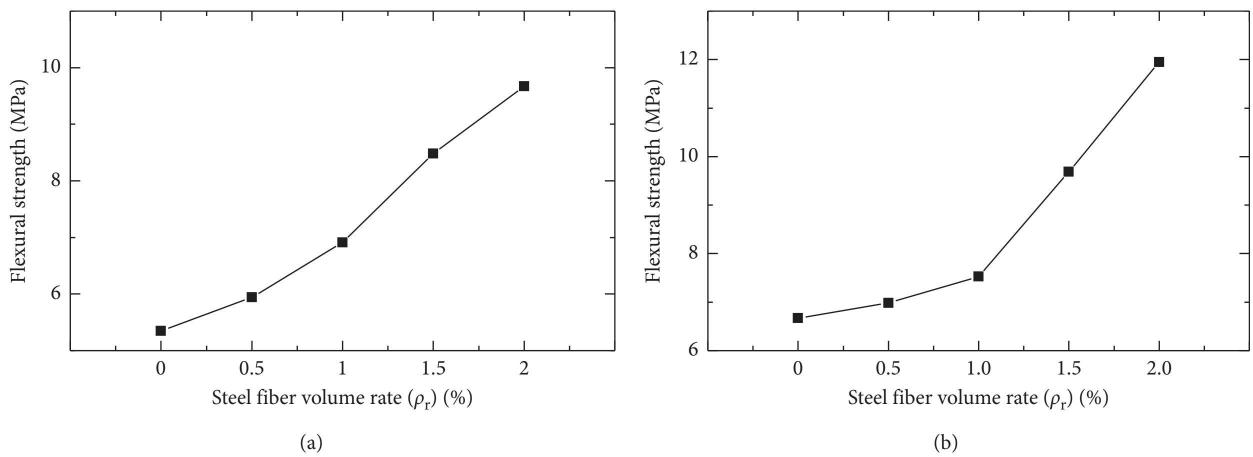


FIGURE 14: Relationship between flexural strength and steel fiber content. (a) CF50; (b) CF60.

the same fiber content of 1.0%, the compressive strength increases by 12.68% and 5.78% in CF60 and CF50, respectively.

4.3. Flexural Properties of Steel Fiber Concrete

4.3.1. Flexural Properties of Steel Fiber Concrete Made by Tradition Mixing Conditions. It can be seen from Figure 14(a) that, for the traditional mixing method, the flexural strength of steel fiber-reinforced concrete CF50 increases obviously as the steel fiber content increases. At the fiber content of 0.5%, 0.75%, 1%, 1.5%, and 2%, the concrete flexural strength increases by 11.03%, 15.14%, 29.22%, 58.50%, and 80.75%. Figure 14(a) also shows that while the fiber content is less than 1%, the flexural strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the flexural tensile strength increases rapidly.

Figure 14(b) shows that, similar to CF50, the flexural strength of steel fiber-reinforced concrete CF60 also improves with the increase of steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete flexural strength increases by 17.91%, 27.02%, 68.24%, and 101.86%. Figure 14(b) also shows that while the fiber content is less than 1%, the flexural strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

Comparing CF50 to CF60, it can be found that, at the same fiber content, fiber reinforcement effect of flexural strength of high-strength concrete CF60 is higher than that of CF50; for example, at the fiber content of 1.5%, the flexural tensile strength increases by 68.24% and 58.50% in CF60 and CF50, respectively. In other words, for traditional stirring, steel fiber enhanced effect of high-strength concrete is more obvious.

4.3.2. Effect of Steel Fiber Content on Flexural Properties of Concrete under Vibratory Mixing. It can be seen from Figure 15(a) that, for the vibratory mixing method, the flexural strength of steel fiber-reinforced concrete CF50 increases obviously as the steel fiber content increases. At the fiber content of 0.5%, 0.75%, 1%, 1.5%, and 2%, the concrete flexural strength increases by 8.06%, 13.82%, 24.51%, 55.76%, and 72.86%. Figure 15(a) also shows that while the fiber content is less than 1%, the flexural strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the flexural tensile strength increases rapidly.

Figure 15(b) shows that, similar to CF50, the flexural strength of steel fiber-reinforced concrete CF60 also improves with the increase of steel fiber content. At the fiber content of 0.5%, 1%, 1.5%, and 2%, the concrete flexural strength increases by 8.45%, 19.75%, 47.82%, and 68.94%. Figure 15(b) also shows that while the fiber content is less than 1%, the flexural strength increases slowly, while the fiber content is more than 1% (e.g., 1.5% and 2.0%), the splitting tensile strength increases rapidly.

4.3.3. Effect of Different Mixing Methods on the Flexural Performance of Concrete. It can be seen from Figure 16(a) that, with the increase of the steel fiber content, the flexural strength of CF50 concrete improves continuously. Comparing to traditional mixing concrete, at the same steel fiber content, the concrete made by vibratory mixing is equipped with higher flexural strength. At the fiber content of 0%, 0.5%, 0.75%, 1%, 1.5%, and 2%, comparing to traditional mixing concrete, the flexural strength of vibratory mixing concrete increases by 13.55%, 10.61%, 12.34%, 9.50%, 11.67%, and 8.69%. Figure 16(a) also shows that, at the fiber content of 0.0%, comparing to traditional mixing, the splitting tensile strength of concrete made by vibratory mixing improves obviously.

Figure 14(b) shows that, similar to CF50, with the increase of the steel fiber content, the flexural strength of CF60 concrete improves continuously. Comparing to traditional mixing concrete, at the same steel fiber content, the concrete made by vibratory mixing is equipped with higher flexural strength. At the fiber content of 0%, 0.5%, 1%, 1.5%, and 2.0%, comparing to traditional mixing concrete, the splitting tensile strength of vibratory mixing concrete increases by 10.01%, 14.04%, 16.73%, 8.94%, and 3.77%. Figure 14(b) also shows that, at the fiber content of 1.0%, comparing to

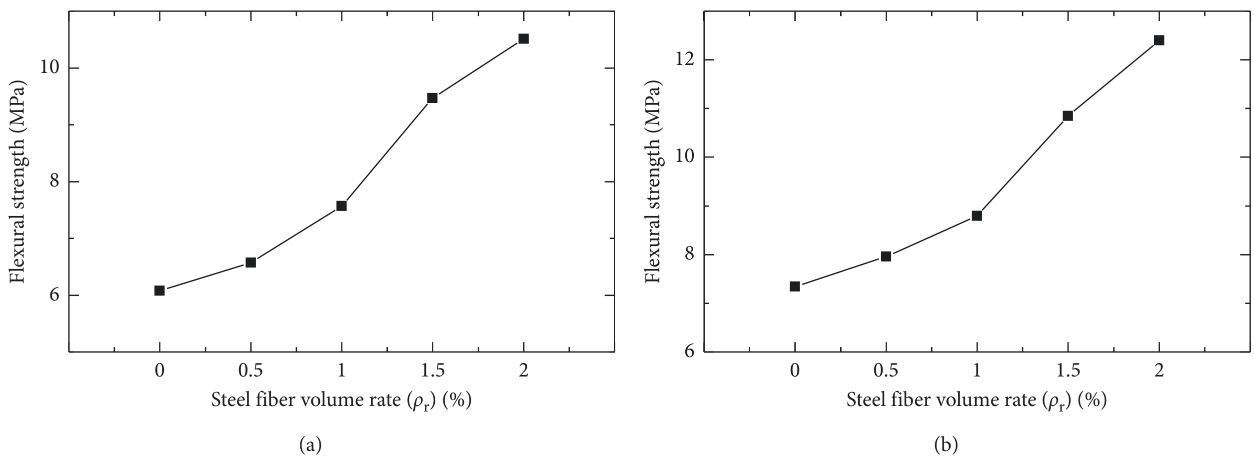


Figure 15: Relationship between flexural strength and steel fiber content. (a) CF50; (b) CF60.

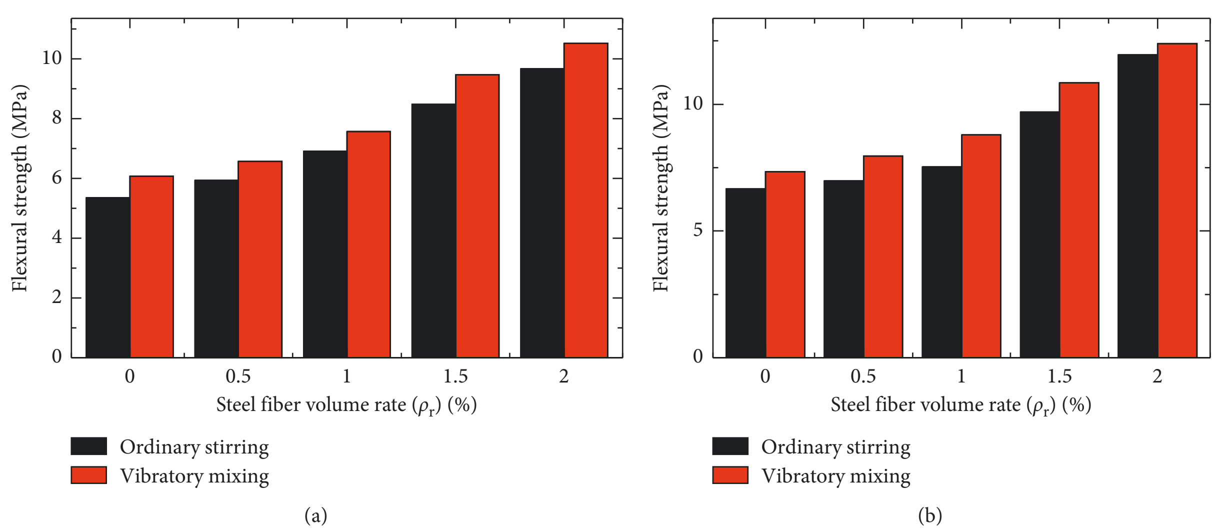


Figure 16: Effect of different mixing methods on the flexural strength of concrete. (a) CF50; (b) CF60.

traditional mixing, the flexural strength of concrete made by vibratory mixing improves obviously.

Comparing CF50 to CF60, it can be found that fiber-reinforced effect of flexural strength of high-strength concrete CF60 is higher than that of CF50; for example, at the same fiber content of 1.0%, the flexural strength increases by 16.73% and 9.50% in CF60 and CF50, respectively.

5. Conclusion

In this paper, the compressive strength, splitting tensile strength, and flexural strength of steel fiber-reinforced concrete made by different mix methods were analyzed. The main conclusions are as follows:

(1) With the increase in steel fiber content, all of these mechanical properties such as compression strength, flexural strength, and splitting tensile strength improve gradually; especially for flexural strength and splitting tensile strength, the steel fiber reinforcement effect is obvious. At the same fiber content, reinforcement effect of mechanical properties of high-strength concrete is better.

(2) The vibratory mixing method can make the steel fiber distribute uniformly in the concrete; as a result, comparing to traditional mixing, the vibratory mixing method can improve the compressive strength, splitting tensile strength, and flexural strength effectively. For example, compressive strength can be improved by 10%, splitting tensile strength can be improved by 15%, and flexural strength can be improved 12%.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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