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Experimental study on the fracture parameters of concrete

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Abstract: This study was aimed to determine the influence of the volume fraction of steel fibers and on fracture parameters of concrete. Fifty notched steel fiber reinforced concrete (SFRC) beams and ordinary concrete beams with dimensions of 100mm×100mm×515mm were cast and tested via three-point bending test. Among them, the type of steel fiber is milling type (MF), and the volume fraction of steel fiber added is 0%, 0.5%, 0.5%, 1.5%, 1.5%, 2%, respectively. The effects of the steel fiber volume fraction (V_F) on the critical stress intensity factor (K_{IC}), fracture energy (G_F), the deflection at failure(δ_0), the critical crack mouth opening displacement (CMOD_c) and the critical crack tip opening displacement (CTOD_c) were studied. Through the analysis of test phenomena and test data such as load-deflection (P- δ) curve, load-crack mouth opening displacement (P-CMOD) curve and load-crack tip opening displacement (P-CTOD) curve following conclusions are drawn: With the increase of steel fiber volume fraction, some fracture parameters increase gradually and maintain a certain linear growth. The gain ratio of fracture parameters increases significantly, and the gain effect is obvious. Through this law of growth, the experimental statistical formulas of fracture energy and critical stress intensity factor are summarized.

Keywords: steel fiber; three-point bending; fracture parameters; gain ratio

1. Introduction

Steel-fiber-reinforced concrete (SFRC) has been emerging as a widely used construction material that is suitable for many structural elements [1,2,3]. SFRC has made its application into industrial and airport pavements, projected concrete members and precast concrete elements reducing the concrete thickness [3,4].

SFRC is a composite material produced by reinforcement of a cementitious matrix in which short length steel fibers are distributed randomly. Compared with ordinary concrete, the incorporation of steel fiber is getting growing interest as it offers many advantages such as tensile strengths, toughness and durability [5-7,9,12,16]. SFRC can effectively make up for the defects of concrete easy to crack [3], improve the mechanical properties of road and promote the development of road construction industry.

The remarkable feature of steel fiber is that it hinders the development of macro cracks, delays the propagation of micro cracks to macro cracks and improves the ductility of micro cracks [1,8-12]. This performance enhancement under tension and bending is mainly due to the better post-cracking behavior of fiber bridging cracks, which leads to much higher energy absorption capacity than ordinary concrete [1,8]. Many researchers that including steel fibers provided higher flexural strength, deflection capacity, and post-peak ductility than plain concrete, and these strength and ductility increases with the increase in the fiber content [2,17]. Through this experiment, it was also

proved that adding steel fiber and increasing the amount of fiber can significantly improve the fracture toughness and energy absorption capacity of concrete.

Fracture performance is important for the safety and durability of concrete structures. A basic ingredient for measuring the fracture process in quasi-brittle materials is the fracture energy (G_F) [1]. F. Bencardino et al. [1] reported that adding fibers in concrete has a major influence on the fracture property and ductility of the FRC. According to Doo-Yeol Yoo et al. [2], Steel fiber content more than 1.0% can significantly improve the flexural strength, flexural capacity and fracture energy of concrete, and these factors will also increase with the increase of steel fiber content. M.T.Kazemi et al. [13] studied the fracture properties of SFHSC and found that the fracture properties of SFHSC increased with the increase of steel fiber content. The above studies show that the content of steel fiber has a significant effect on the properties of concrete.

In the literature, different methods have been proposed for estimating the fracture parameters experimentally: the direct uniaxial tension test, the wedge splitting test, and bending tests [1]. In order to ensure the uniform mixing of steel fibers with different volume fraction, it is necessary to increase water consumption in different degrees, in order to eliminate the influence of matrix concrete strength variation on the test results and objectively reflect the gain effect of steel fiber on the mechanical properties of SFRC, the concept of gain ratio is introduced based on the study of SFRC fracture parameters. The gain ratio is the ratio between the fracture parameters of SFRC and the fracture parameters of FRC specimens poured with the corresponding mixture proportion. Three-point bending test was used to evaluate the effect of fiber content on the fracture parameters of SFRC, and the effect was explained by experimental phenomena, test process curve and calculated gain ratio. Two test statistical equations of V_F-G_F and V_F-K_{IC} are established respectively, where $R^2=0.97$ and 0.99. This study can further promote the understanding and application of steel fiber reinforced concrete.

2. Summary of test

2.1. Materials

According to CECS13:89 [14], in this test, PO42.5 Portland cement was selected, mid-coarse river sand with a modulus of fineness of 3.39, and limestone with a maximum particle size of 20mm and continual size distribution. FDN-1 high efficiency water reducing agent with 1% cement dosage was also used. The milling steel fiber with a length-diameter ratio of 34.42 was adopted. The milling steel fiber fraction was variable, consisting of 0,0.5%,1.0%,1.5% and 2%, respectively.

2.2. Mix design

According to CECS13:89 [14], the reference concrete mix proportion is $m(\text{water}): m(\text{cement}): m(\text{sand}): m(\text{stone}) = 164: 341.7: 661.1: 1283.3: 1.64$. In order to ensure the uniform mixing of steel fiber, the water consumption increased by 10 kg from the reference concrete group to the fiber concrete group. For every 0.5% increase in V_F , water consumption increased by 8 kg. In order to eliminate the influence of strength variation of matrix concrete on the test results, at the same time of pouring SFRC, the ordinary concrete (OC) specimens with the same mix proportion as SFRC but without steel fiber were used as contrast specimens. The mix proportion of SFRC specimen and contrast group concrete is shown in Table 1.

Table 1. Mix proportion of steel fiber reinforced concrete (SFRC) and ordinary concrete (OC)

| Mix No | Cement (kg/m3) | Water (kg/m3) | Sand (kg/m3) | Stone (kg/m3) | FDN-1 (kg/m3) | Steel fiber content (kg/m3) |
|--------|----------------|---------------|--------------|---------------|---------------|-----------------------------|
| MF00 | 341.7 | 164.0 | 661.1 | 1283.3 | 3.42 | 0.0 |
| MF05 | 358.3 | 172.0 | 748.7 | 1171.0 | 3.58 | 39.3 |
| MF05-0 | 358.3 | 172.0 | 748.7 | 1171.0 | 3.58 | 0.0 |
| MF10 | 375.0 | 180.0 | 795.9 | 1099.1 | 3.75 | 78.6 |

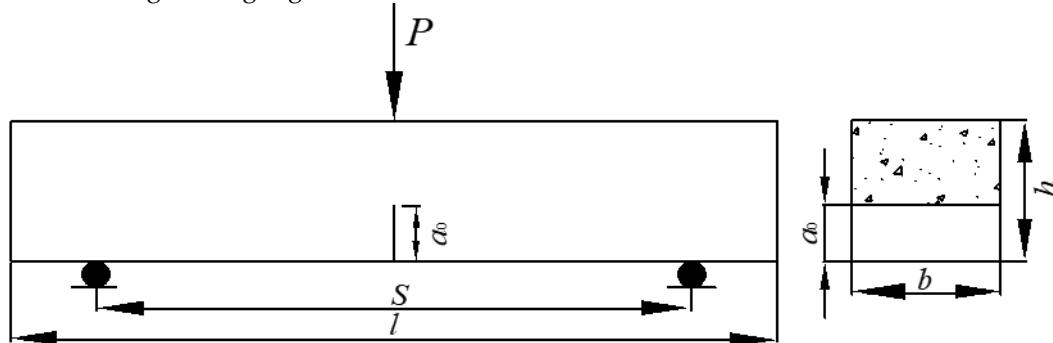
Table 1. Cont.

| Mix No | Cement (kg/m3) | Water (kg/m3) | Sand (kg/m3) | Stone (kg/m3) | FDN-1 (kg/m3) | Steel fiber content (kg/m3) |
|--------|----------------|---------------|--------------|---------------|---------------|-----------------------------|
| MF10-0 | 375.0 | 180.0 | 795.9 | 1099.1 | 3.75 | 0.0 |
| MF15 | 391.7 | 188.0 | 841.7 | 1028.7 | 3.92 | 117.9 |
| MF15-0 | 391.7 | 188.0 | 841.7 | 1028.7 | 3.92 | 0.0 |
| MF20 | 408.3 | 196.0 | 885.9 | 959.7 | 4.08 | 157.2 |
| MF20-0 | 408.3 | 196.0 | 885.9 | 959.7 | 4.08 | 0.0 |

¹The number represents 10 times the fiber content, and ' - 0' is the test contrast group specimen. For example, 'MF15-0' represents the contrast group of $V_F=1.5\%$ milling steel fiber reinforced concrete specimens. MF00 is the reference group of concrete specimens.

2.3. Specimen preparation procedure

Notched three-point bending beams as shown in Figure 1. The specimens were 100mm wide, 100mm high and 515mm long, the span S is 400mm, the relative notch depth of the specimens, a_0/l , was 0.4. The design strength grade of SFRC is FC30.

**Figure 1.** Sketch of specimen shape and dimension

In order to improve the uniformity of the mixture of SFRC and control group ordinary concrete (OC) specimens and avoid segregation, superplasticizer was used and the mixing time was prolonged. In order to make the fiber well distributed and avoid agglomeration, the slow dispersion method is adopted when adding steel fiber, and a forced mixer is used. The concrete of SFRC and its contrast group was mixed by forced mixer, formed by shaking table, cured in the standard curing room (temperature $20\pm3^\circ\text{C}$, relative humidity not less than 95%) for 28 days, and then naturally cured and processed to the test room after maintenance. Experimental age 50d~70d.

3. Test method

3.1 The three-point bending test

The three-point bending test was carried out on a hydraulic press testing machine with a maximum capacity 2000kN. In order to ensure the continuous stability of the test process, the disc spring reinforcement device of the testing machine was used to strengthen the testing machine. The load sensor is used to measure the load of notched three-point bending beam, and the measuring range of the sensor is 0~30kN. In order to eliminate the influence of bearing deformation on the

deflection test results, the deflection test beam was arranged directly above the support point of the three-point bending specimen, and the mid-span deflection is measured with a percentile meter. The CMOD clip extensometer was arranged at the bottom of the beam with a 3mm thick alloy aluminum knife edge. The CTOD clip extensometer was fixed at the tip of the crack on the side of the beam with a knife edge.

The continuous loading mode was adopted in the test, and the computer data acquisition system was used to realize the automatic data acquisition. The acquisition rate was different according to the type of the component, such as concrete component 2 times / s, SFRC component 1 time / s. The load deflection ($P - \delta$) curve, load - CMOD ($P - \text{CMOD}$) curve and load - CTOD ($P - \text{CTOD}$) curve can be observed simultaneously. According to these test curves and the observation of test phenomena during the test, the fracture properties of SFRC can be analyzed qualitatively and quantitatively. The experimental loading and measurement device can be seen in Figure.2.

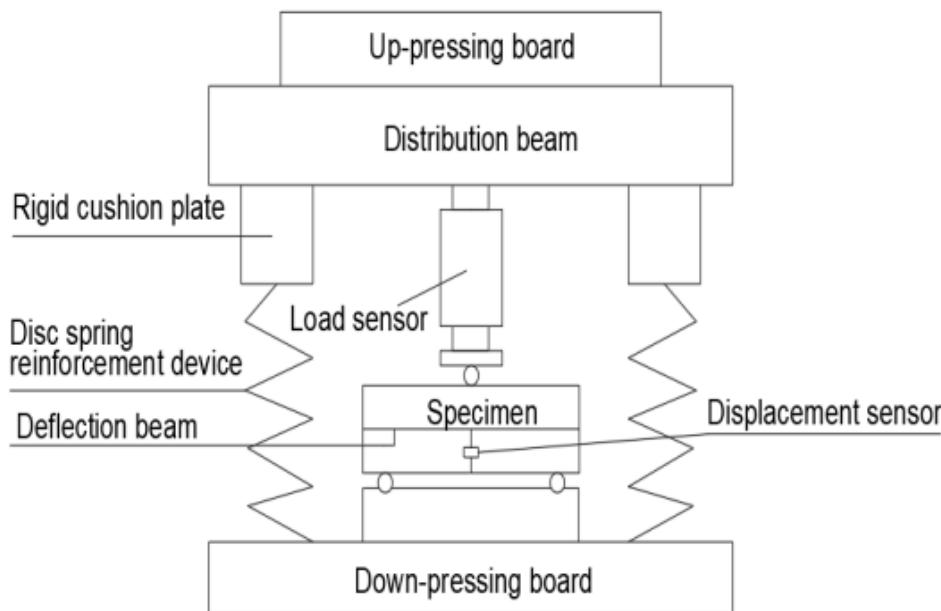


Figure 2. Sketch of loading set-up for three-point bending test

3.2 Calculation formula of fracture parameters

3.2.1 Calculation formula of critical stress intensity factor (K_{IC}):

In China, the K_{IC} calculation formula in ASTM E399-1972 is often used. The calculation formula of K_{IC} is as follow:

$$K_{IC} = \frac{P_{max}S}{bh^{1.5}} f\left(\frac{a}{h}\right) \quad (1)$$

$$f\left(\frac{a}{h}\right) = 2.9\left(\frac{a}{h}\right)^{0.5} - 4.6\left(\frac{a}{h}\right)^{1.5} + 21.8\left(\frac{a}{h}\right)^{2.5} - 37.6\left(\frac{a}{h}\right)^{3.5} + 38.7\left(\frac{a}{h}\right)^{4.5} \quad (2)$$

where, P_{max} is the measured maximum load [N], S is the span of beam [mm], b is the width of sample [mm], h is the height of sample [mm], a is the actual crack length [mm], and the virtual crack length is used in this paper.

3.2.2 The calculation formula of fracture energy (G_F) [10,15]:

$$G_F = \frac{W_0 + mg\delta_0}{b(h-a_0)} \quad (3)$$

where W_0 is the area under the load-deflection curve [$\text{N} \cdot \text{m}$], m is the total mass of specimen between supports [kg], g is the gravitational constant [N/kg], δ_0 is the deflection at failure [mm], h is the height of the sample [mm], a_0 is the depth of the notch [mm] and b is the width of the sample [mm].

4. Test results and analysis

The testing results of fracture parameters of SFRC and OC are shown in Table 2. All test results were reported as the average value of tested specimens.

In the correlation analysis of this paper, the gain ratio is used to reflect the reinforcement effect of steel fiber, which is defined as: gain ratio = mechanical performance index of SFRC / mechanical performance index of corresponding contrast group concrete specimen. For example: fracture toughness gain ratio = fracture toughness of SFRC specimens / fracture toughness of OC specimens of the same mix proportion.

Table 2. Testing results for fracture parameters of SFRC and ordinary concrete

| Mix No | V_F (%) | P_{max} (kN) | K_{IC} MPa·m ^{1/2} | K_{IC} gain ratio | GF (N·m ⁻¹) | G_F gain ratio | CMOD _C (mm) | CTOD _C (mm) | δ_0 (mm) |
|--------|-----------|----------------|-------------------------------|---------------------|-------------------------|------------------|------------------------|------------------------|-----------------|
| MF00 | 0.0 | 3.1802 | 1.7006 | - | 181.410 | - | 0.0618 | 0.0324 | 0.0893 |
| MF05 | 0.5 | 3.3151 | 2.2146 | 1.43 | 1043.8433 | 5.88 | 0.0997 | 0.0566 | 0.1203 |
| MF05-0 | 0.0 | 2.7759 | 1.5493 | - | 177.3862 | - | 0.0645 | 0.0397 | 0.1068 |
| MF10 | 1.0 | 3.6335 | 2.9164 | 1.84 | 1786.4485 | 9.86 | 0.1739 | 0.0996 | 0.1894 |
| MF10-0 | 0.0 | 2.8952 | 1.5884 | - | 181.1768 | - | 0.0656 | 0.0377 | 0.1076 |
| MF15 | 1.5 | 4.6427 | 4.3073 | 2.38 | 2331.9664 | 15.27 | 0.2638 | 0.1446 | 0.3450 |
| MF15-0 | 0.0 | 2.9000 | 1.8067 | - | 152.7245 | - | 0.0789 | 0.0330 | 0.0831 |
| MF20 | 2.0 | 6.1080 | 5.3880 | 3.45 | 3264.4605 | 20.52 | 0.3060 | 0.1692 | 0.3941 |
| MF20-0 | 0.0 | 2.7034 | 1.5616 | - | 159.0965 | - | 0.0629 | 0.0326 | 0.0807 |

4.1 Fracture toughness

The effect of V_F on K_{IC} is shown in Figure 2. It can be seen compared with the reference group concrete, the addition of steel fiber significantly improves the fracture toughness of SFRC, and with the increase of V_F , the K_{IC} of SFRC specimens shows a good increasing trend. For every 0.5% increase in fiber fraction, the average increase in K_{IC} is 33.7%. The K_{IC} gain ratio of V_F to SFRC can be seen from the Table 2: with the addition of steel fiber, the K_{IC} gain ratio of SFRC specimens is greater than 1, and with the increase of V_F , the gain ratio shows a good increasing trend, the minimum gain ratio is 1.43, the maximum gain ratio is 3.45, and the average gain ratio is 2.275. Therefore, it can be considered that the addition of steel fiber improves the K_{IC} of concrete.

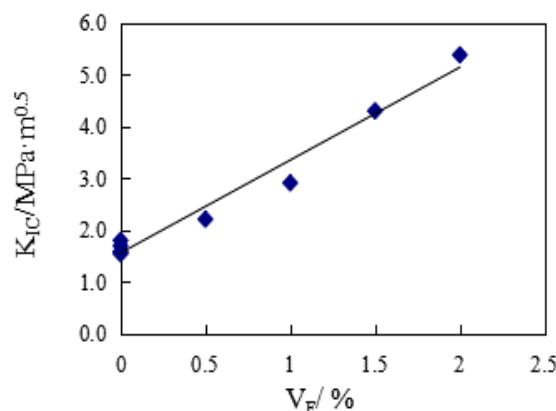


Figure 3. The effect of V_F on K_{IC}

According to the test results of K_{IC} in this paper, the statistical analysis shows that:

$$K_{IC} = 1.7925V_F + 1.5634 \quad (4)$$

where $R^2=0.9748$. It can be seen the increase of K_{IC} is mainly affected by V_F .

The failure patterns of three-point bending specimens with different V_F are compared, as shown in the Figure 4 and Figure 5.



Figure 4. The failure of OC

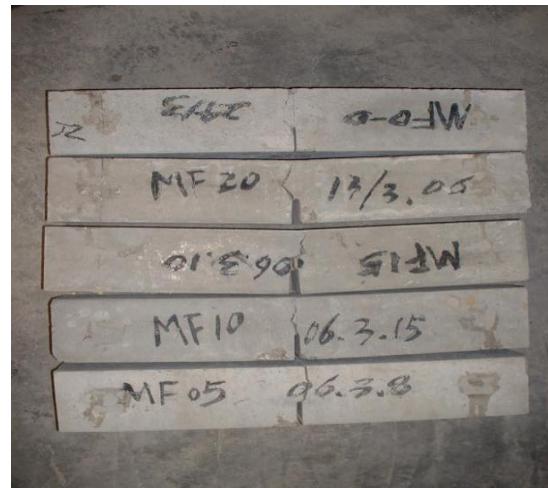


Figure 5. The failure of SFRC

It can be seen from the test process that the SFRC specimen can hear sound of fiber pulling out or breaking clearly in the test. E.K. Tschegg [18] also got similar results. With the addition of steel fiber, the crack development path becomes relatively tortuous, from the single crack propagation of the reference group to the multi-point cracking of more than one crack, and with the increase of V_F , the crack propagation path becomes more tortuous. Except for a small number of SFRC specimens with small content, some of them were split in half, but most of the specimens were not completely split, which kept the integrity to a certain extent. On the other hand, the K_{IC} of ordinary concrete of reference group and contrast group is not only small, but also the bearing capacity of specimens decreases rapidly after the test load reaches the peak, and most of the specimens are split into two parts. It can be judged that the addition of steel fiber greatly improves the fracture toughness of SFRC.

4.2 Fracture energy

Figure 6. shows the effect of V_F on G_F of SFRC. It can be seen compared with the reference group concrete, the addition of steel fiber greatly improves the fracture energy of concrete matrix, and with the increase of V_F , G_F keeps an obvious linear increasing trend. For every 0.5 percentage point increase in V_F , G_F increases between 30.53% and 71.14%, with an average increase of 47.22%. It can be seen from the Table 2. that compared with the contrast group concrete, the G_F gain ratio of SFRC specimens is between 5.88 and 20.52, and the average gain ratio is 12.88. It can be seen the addition of steel fiber greatly improves the energy absorption capacity of concrete matrix.

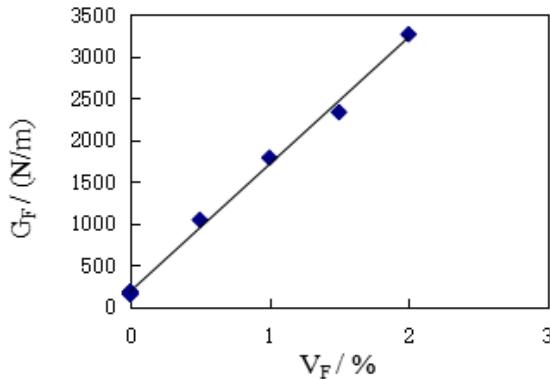


Figure 6. The effect of V_F on G_F

According to the test results of KIC in this paper, the statistical analysis shows that:

$$G_F = 1520.6V_F + 186.18 \quad (5)$$

where R²=0.9966. It can be seen the increase of G_F is mainly affected by V_F.

Figure 7. shows the comparison of typical load deflection (P- δ) curves of a group of experiments under different V_F conditions.

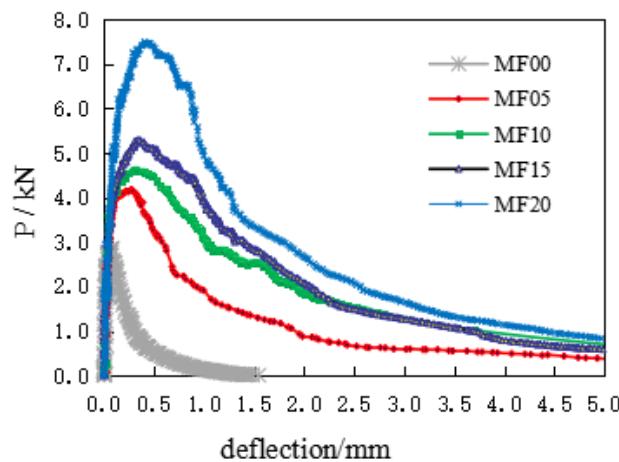


Figure 7. The typical load-deflection curves

It can be seen from the figure that the deflection of concrete specimen is almost linear elastic before reaching the peak load. This result is consistent with the test results of Doo-Yeol Yoo [2]. As the load continues to increase, the deformation of the matrix concrete reaches the initial crack strain, the concrete matrix appears micro-cracks, and P- δ curves begin to show a non-linear growth. With the emergence of macroscopic cracks, the matrix concrete cracks continue to expand, and the steel fiber reinforced concrete is in the elastic-plastic stage. At this time, in the process of gradually pulling out, the steel fiber connects the concrete across the cracks, so that the steel fiber reinforced concrete shows better ductility. With the increase of V_F, the number of fibers across the cracks increases accordingly, and the ability to transfer stress is also relatively improved. The microcracks in the fracture process zone develop fully, and the absorbed external load energy increases accordingly, which is characterized by the increase of the peak load and ultimate deflection of the specimen, the test curve becomes fuller, and the improvement of fracture performance is more sufficient.

4.3 Crack opening displacement

From the test data analysis Table 2, it can be seen compared with the reference group concrete specimens, the addition of steel fiber increases CMOD_c and CTOD_c of matrix concrete, and with the increase of V_f, CMOD_c increases linearly, and the deflection corresponding to CMOD_c also increases obviously.

The typical load-CMOD diagram and load-CTOD diagram of a group of SFRC specimens recorded during the bending test is shown in Figure 8 and Figure 9. It can be seen from the figure that the crack opening displacement of the ordinary concrete specimen is almost linear elastic before reaching the peak load, and the crack opening displacement of the fiber reinforced concrete specimen also shows linear elasticity at the initial stage of applying the load, and gradually enters the plastic stage with the continuous increase of the load, which is an extensive cracking process, which is obviously different from the ordinary concrete specimen.

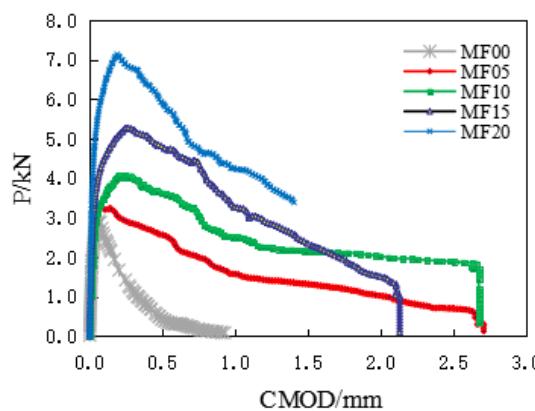


Figure 8. The typical load-CMOD curves

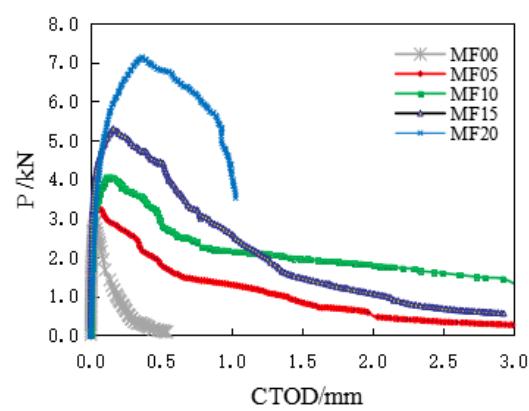


Figure 9. The typical load-CTOD curves

With the increase of the load, the steel fiber is gradually pulled out, and it connects the concrete across the cracks, and the high content of steel fiber increases the bridging effect, which makes the steel fiber reinforced concrete show better ductility. In the test, the peak load and critical crack opening displacement of concrete specimens increased.

5. Conclusions

Through the analysis of the fracture behavior of concrete notched three-point bending beam specimens of SFRC and its contrast group, the following conclusions can be drawn:

1. The addition of steel fiber to concrete can obviously improve the fracture toughness of concrete. With the increase of V_f, the K_{IC} of SFRC specimens showed a good increasing trend. For every 0.5% increase in fiber volume rate, the average increase of K_{IC} is 33.7%, and the average gain ratio is 2.275.
2. Adding steel fiber to concrete can obviously improve the fracture energy of concrete. With the increase of V_f, the G_F and G_F gain ratio of SFRC specimens showed a good increasing trend. In the range of V_f, for every 0.5% increase of V_f, the average gain ratio of G_F is 47.22%, and the average gain ratio is between 5.88 and 20.52, and the average gain ratio is 12.88.
3. With the addition of steel fiber, the peak loads, the deflection at failure and the critical crack opening displacement of concrete specimens increased.
4. Two test statistical equations of V_f-G_F and V_f-K_{IC} are established respectively, where R²=0.97

and 0.99.

References

1. Bencardino, F.; Rizzuti, L.; Spadea, G.; Swamy, N.R. Experimental evaluation of fiber reinforced concrete fracture properties. *Composites Part B* **2009**, *41*, 17-24.
2. Yoo, D.Y.; Yoon, Y.S.; Banthia, N. Predicting the post-cracking behavior of normal- and high-strength steel-fiber-reinforced concrete beams. *Construction and Building Materials* **2015**, *93*, 477-485.
3. Iqbal, S.; Ali, I.; Room, S.; Khan, S.A.; Ali, A. Enhanced mechanical properties of fiber reinforced concrete using closed steel fibers. *Materials and Structures* **2019**, *52*, 1-10.
4. Prisco, M.D.; Lamperti, M.; Lapolla, S.; Khurana, R. HPFRCC thin plates for precast roofing. In Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel, Germany, 5-7 March 2008.
5. Xu, B.W.; Shi, H.S. Correlations among mechanical properties of steel fiber reinforced concrete. *Construction and Building Materials* **2009**, *23*, 3468-3474.
6. Thomas, J.; Ramaswamy, A. Mechanical Properties of Steel Fiber-Reinforced Concrete. *Journal of Materials in Civil Engineering* **2007**, *19*, 385-392.
7. Ramadoss, P.; Nagamani, K. Investigation on the tensile strength of high-performance fiber reinforced concrete using statistical methods. *Computers & Concrete* **2006**, *3*, 389-400.
8. Luo, X.; Sun, W.; Chan, S.Y.N. Characteristics of high-performance steel fiber-reinforced concrete subject to high velocity impact. *Cement and Concrete Research*, **2000**, *30*, 907-914.
9. Şahin, Y.; Köksal, F. The influences of matrix and steel fibre tensile strengths on the fracture energy of high-strength concrete. *Construction and Building Materials* **2010**, *25*, 1801-1806.
10. Chen, B.; Liu, J. Effect of aggregate on the fracture behavior of high strength concrete. *Construction and Building Materials* **2004**, *18*, 585-590.
11. Kurihara, N.; Kunieda, M.; Kamada, T.; Uchida, Y.; Rokugo, K. Tension softening diagrams and evaluation of properties of steel fibre reinforced concrete. *Engineering Fracture Mechanics* **2000**, *65*, 235-245.
12. Bencardino, F.; Rizzuti, L.; Spadea, G.; Swamy, R.N. Implications of test methodology on post-cracking and fracture behaviour of Steel Fibre Reinforced Concrete. *Composites Part B: Engineering* **2013**, *46*, 31-38.
13. Kazemi, M.T.; Golsorkhtabar, H.; Beygi, M.H.A.; Gholamitabar, M. Fracture properties of steel fiber reinforced high strength concrete using work of fracture and size effect methods. *Construction and Building Materials* **2017**, *142*, 482-489.
14. Standard of China Engineering Construction Standardization Association of the People's Republic of China. *Test method for steel fiber reinforced concrete*, CECS13:89; China Planning Press: Beijing, China, 1989.
15. Siregar, A.P.N.; Rafiq, M.I.; Mulheron, M. Experimental investigation of the effects of aggregate size distribution on the fracture behaviour of high strength concrete. *Construction and Building Materials* **2017**, *150*, 252-259.
16. Holschemacher, K.; Mueller, T.; Ribakov. Effect of steel fibres on mechanical properties of high-strength concrete. *Materials & Design* **2009**, *31*, 2604-2615.
17. Beigi, M.H.; Berenjian, J.; Omran, O.L.; Nik, A.S.; Nikbin, I.M. An experimental survey on combined effects of fibers and nanosilica on the mechanical, rheological, and durability properties of self-compacting concrete. *Materials & Design* **2013**, *50*, 1019-1029.
18. Tschegg, E.K.; Schneemayer, A.; Merta, I.; Rieder, K.A. Energy dissipation capacity of fibre reinforced concrete under biaxial tension-compression load. Part II: Determination of the fracture process zone with the acoustic emission technique. *Cement and Concrete Composites* **2015**, *62*, 187-194.