Experimental Research on Mechanical Properties of Steel-UHMWPE Hybrid Fiber Reinforced Concrete

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Abstract. The mechanical properties of a new type of hybrid fiber reinforced concrete (HFRC) which was reinforced by the steel fiber and the ultra-high molecular weight polyethylene (UHMWPE) fiber were researched. The effects of the fiber hybrid ratio on the strength and cracking-resistance properties of concrete were studied through the split-tensile and the cubic-compression tests on 16 types of HFRC. The result shows that the hybrid of the steel fiber and UHMWPE fiber can play a multi-layered role in crack-resistance properties of concrete. The strengths of HFRC is further increased when the UHMWPE fiber are mixed on the basis of the steel fiber. When the fiber volume content of UHMWPE is extra added by 0.3%, the tensile strength increases by 13.64%, 49.49% or 8.08%, and the compressive strength increases by 13.51%, 15.49% or 14.57% compared with the single steel fiber reinforced concrete as the fiber content is 0.5%, 1.0% or 1.5%. The UHMWPE fiber has more obvious effects on material strength compared with polypropylene fiber when it is mixed with the steel fiber reinforced concrete.

1. Introduction

It has been found that the dispersion of certain short fiber in concrete can improve the crack resistance properties and enhance the strength and toughness [1, 2, 3]. However, the improvement of fiber reinforced concrete depends mainly on the properties of fiber. Different fiber and fiber parameters have a great influence on the effects of reinforcement [4]. Therefore, it is a hot spot of recent researches to improve the mechanical properties of fiber reinforced concrete more comprehensively by mixing many kinds of fiber or fiber with different characteristic sizes [5].

C.Q.Wang introduced a coefficient to study the effect of different geometrical fiber hybrid on concrete [6]. In terms of different fiber shapes, Y.Zhang studied the effect of corrugated steel fiber, end-hook steel fiber and polypropylene fiber on the compressive strength when the two of them were hybrid [7]. At present, the researches on the hybrid fiber in different properties are still dominated by steel fiber and polypropylene fiber. L.H.Xu introduced the fiber eigenvalues to carry on regression analysis in the mechanical properties of steel-polypropylene HFRC [8]. Z.P.Dong found that steel fiber can significantly improve the strength of concrete while polypropylene fiber can only improve the toughness of concrete due to the limitation in the fiber strength [9].
UHMWPE fiber is a kind of flexible fiber with high modulus and strengths. Its effects of enhancement on concrete are more significant compared with other flexible fiber such as polypropylene fiber [10]. In this paper, the mechanical properties of steel-UHMWPE HFRC were studied with 16 fiber hybrid ratios designed. The effects of the two fiber hybrid on concrete strength and crack-resistance performance were studied by the split-tensile and the cubic-compression tests.

2. Overview of the Tests

2.1. Mixture Ratio

The matrix concrete was designed at the grade of C70. The mixture ratio is as follows: water cement ratio 0.326, sand content 40%, water reducer content 1.6%, and the silica fume content 9.5%. The specific ratio is shown in Table 1.

Steel fiber and UHMWPE fiber were designed at four volume content levels, respectively into 0%, 0.5%, 1.0%, 1.5% and 0%, 0.1%, 0.2%, 0.3%, for a total of 16 fiber hybrid groups. The lables of the test groups were unified as SxPy where S is the abbreviation of steel fiber and P the abbreviation of UHMWPE fiber as well. The subscript x, y represent the volume content of steel fiber and UHMWPE fiber (%).

| Water | P.O 42.5 Cement | Stone | Sand | Silica fume | Water reducer |
|-------|-----------------|-------|------|-------------|---------------|
| 185   | 547             | 936   | 615  | 57.5        | 12            |

2.2. Material and Test Pieces

Steel fiber: Strength Q195, End hook type, Diameter 0.5mm, Length 30mm, Tensile strength 1200MPa, Elastic modulus 200GPa, Density 7.8g/cm³, Ultimate elongation 2.0%, as shown in Fig.1(a).

UHMWPE fiber: Monofilament diameter 60μm, Length 30mm, Tensile strength 3000MPa, Elastic modulus 100GPa, Density 0.97 g/cm³, Ultimate elongation 3.2%, as shown in Fig.1(b).

According to the specification for concrete tests [11], the splitting-tensile and cubic-compression tests adopt 150mm standard cubic specimens with 3 for each test. After casting, the specimens were shaken for 2 minutes, plastered and formed. After 24 hours on the horizontal plane, the specimens were maintained for 28 days in a standard maintenance room with the temperature of (20±2)℃ and the humidity of 95%.

2.3. Test Method

The tests were completed by using an electro-hydraulic servo universal testing machine. The splitting-tensile test was uniformly loaded at the rate of 0.08 MPa/s and the cubic-compression test was loaded at the rate of 0.8 MPa/s until the test pieces were broken. Then the compressive and tensile strength of the test pieces were obtained, and the failure modes were observed.
3. Results and Analysis

3.1. Analysis of Failure Mode

The typical failure mode of the HFRC (S1.5P0.3) in splitting-tensile tests is shown in Fig.2. The process to the complete destruction can be divided into five stages: In stage I, the matrix concrete, the steel fiber and the UHMWPE fiber were all in the elastic deformation stage. And the primary micro cracks remained substantially original form. In stage II, the micro cracks expanded which were suppressed by the uniformly dispersed UHMWPE fiber. In stage III, the micro cracks continued to expand and connect, forming distinct continuous cracks while the steel fiber and UHMWPE fiber synergistically prevented the further development of cracks. In stage IV, UHMWPE fiber were broken due to the limitation of the monofilament in size and strength while the cracking region maintained a certain strength and ductility owing to the presence of steel fiber. In the V stage, steel fiber were pulled out or broken, and the material was completely destroyed.

The result shows that the steel-UHMWPE hybrid fiber have similar crack-resistance mechanism to concrete reinforced by rigid fiber and flexible fiber in hybrid [8]. The effects of fine UHMWPE fiber are mainly to weaken the early expansion of primary crack in concrete and decrease the stress concentration at the tip of crack. Steel fiber which is more coarse play the role of "skeleton" with high strength and anchoring force, because of which the material can maintain a certain bearing capacity and ductility after the macro crack is generated. Typical failure modes of plain concrete (S0P0), UHMWPE fiber reinforced concrete (S0P0.3), steel fiber reinforced concrete (S1.5P0) and HFRC (S1.5P0.3) are shown in Fig.3 and Fig.4.

Figure 2. Typical failure process of the HFRC (S1.5P0.3).

Figure 3. Failure mode of splitting-tensile tests.
UHMWPE fiber inhibit cracks mainly in stages I~III while steel fiber mainly in stages III~IV. Due to the lack of buffer in stages II~IV, the plain concrete (S0P0) was destroyed rapidly and suddenly. UHMWPE fiber reinforced concrete had better control of crack size but it would quickly lose its ability to continue bearing load after reaching the peak. It’s difficult for steel fiber reinforced concrete to control the development of micro cracks in the initial stage. Therefore the final crack size was large while it could still maintain a certain bearing capacity after reaching the peak. HFRC not only had better crack-resistance performance, but also had a significantly enhanced ductility. The two kinds of fiber can synergistically inhibit cracks in multi-stages and multi-layers.

### 3.2. Strength Parameters
Average strengths of all kinds of concrete in splitting-tensile tests and cubic-compression tests are shown in Table 2 where $\eta_t$ and $\eta_c$ respectively indicate the improvement rate compared with the strength of plain concrete (S0P0). 0.3% UHMWPE fiber can increase the tensile strength and compressive strength by 28.54% and 18.30% with its excellent mechanical properties. And the strength of UHMWPE fiber reinforced concrete is significantly higher than that of polypropylene fiber reinforced concrete [10]. Steel fiber plays a major role in the increasing of concrete strength. The tensile strength and compressive strength can increase by 142.17% and 19.24% as the steel fiber content is 1.5%. The hybrid of the two kinds of fiber has further positive effects on concrete strength compared with the case of single fiber. Extra hybrid of 0.3% UHMWPE fiber can increase $\eta_t$ by 13.64%, 49.49% and 8.08%, and $\eta_c$ by 13.51%, 15.49% and 14.57% respectively when the steel fiber content is 0.5%, 1.0% and 1.5%.

| Label  | $f_t$/MPa | $\eta_t$/% | $f_c$/MPa | $\eta_c$/% | Label  | $f_t$/MPa | $\eta_t$/% | $f_c$/MPa | $\eta_c$/% |
|--------|-----------|------------|-----------|------------|--------|-----------|------------|-----------|------------|
| S0P0   | 3.96      | 0.00       | 65.91     | 0.00       | S1.0P0 | 7.98      | 101.52     | 77.21     | 17.15      |
| S0P0.1 | 4.24      | 7.07       | 67.01     | 1.67       | S1.0P0.1 | 6.96      | 75.76      | 73.59     | 11.65      |
| S0P0.2 | 5.51      | 39.14      | 68.70     | 4.23       | S1.0P0.2 | 9.59      | 142.17     | 78.59     | 19.24      |
| S0P0.3 | 5.90      | 28.54      | 77.97     | 18.30      | S1.0P0.3 | 9.94      | 151.01     | 87.42     | 32.64      |
| S0P0.5  | 6.34      | 60.10      | 70.68     | 7.24       | S1.5P0  | 9.59      | 142.17     | 82.76     | 25.56      |
| S0.5P0  | 6.77      | 70.96      | 84.15     | 27.67      | S1.5P0.1 | 9.47      | 139.14     | 82.83     | 25.67      |
| S0.5P0.2 | 6.78     | 71.21      | 85.82     | 30.21      | S1.5P0.2 | 9.30      | 134.85     | 89.87     | 36.35      |
| S0.5P0.3 | 6.88     | 73.74      | 79.59     | 20.75      | S1.5P0.3 | 9.91      | 150.25     | 92.36     | 40.13      |

### 4. Comparison and Analysis

#### 4.1. Comparison with steel-polypropylene HFRC
Fig.5 and Fig.6 show the change rule of $\eta_t$ and $\eta_c$ with the content of different flexible fiber in the references.
From Fig.5, polypropylene fiber has little effects on the tensile strength of the material, and the strength decreases slightly when the content of steel fiber is 1.0% and 1.5%. When the content of steel fiber is 0.5%, the strength increases steadily with the addition of UHMWPE fiber, and the growth rate is greater than polypropylene fiber. When the steel fiber content is 1.0% and 1.5%, the strength decreases at first and then increases because flexible fiber is easy to mix unevenly while fiber overlap and interference each other [13], which cause a decrease in strength. But when the content of UHMWPE fiber is 0.3%, the strength of steel-UHMWPE HFRC is obviously higher than that of steel-polypropylene HFRC.

From Fig.6, the compressive strength of the material has a certain fluctuation with the addition of polypropylene fiber, but the change trend under steel fiber content is consistent. When the polypropylene fiber content is 0.2%, the strength is increased, but the maximum increase is not more than 9%. When the content is 0.1% or 0.3%, the material strength increases little or slightly. The data in this paper show that when the steel fiber content is 0.5%, the material strength increases obviously under different UHMWPE fiber content, and the maximum increase can reach 22.97%. When the steel fiber content is 1.0% and 1.5%, the strength decreases slightly first and then increases significantly, which is similar to the trend of tensile strength. When the content of UHMWPE fiber is 0.3%, the compressive strength of HFRC is obviously higher than that of steel-polypropylene HFRC under different steel fiber content.

4.2. Hybrid Effects
It is pointed out by composite material strengthening theory that the properties of composite materials are additive values of various phases [14]. By analyzing the data in Table 2, the influence equation of fiber hybrid ratio on strength is established as Eq.1:

\[ f = f_0(1 + \alpha_s V_s + \beta_p V_p) \]  \hspace{2cm} (1)

Where
- \( \alpha_s, \beta_p \) —— The strength coefficient of steel fiber and UHMWPE fiber
- \( V_s, V_p \) —— The volume content of steel fiber and UHMWPE fiber (%)
- \( f, f_0 \) —— The strength of HFRC and concrete matrix (MPa)

Regression analysis of the splitting-tensile and cubic-compression strength is shown in Fig.7 and Fig.8 where the equation for calculating strengths can be obtained as Eq.2 and Eq.3.

\[ f_t = f_{to}(1 + 0.884V_s + 1.228V_p) \]  \hspace{2cm} (2)
In the range of fiber content designed in this paper, both Eq.2 and Eq.3 have positive values of $\alpha_s$ and $\beta_p$. Besides the values of $\alpha_s$ and $\beta_p$ in Eq.2 are greater than those in Eq.3. It is shown that the hybrid of steel fiber and UHMWPE fiber plays a good role in enhancing the concrete, and the increase of splitting-tensile strength is obviously greater than the compressive strength, which is consistent with the situation mentioned above. The values of $\beta_p$ in Eq.2 and Eq.3 are greater than $\alpha_s$, and even reach 3.46 times in Eq.3. It shows that the effects of UHMWPE fiber on the strength are significantly higher than that of steel fiber under unit conditions, which proves that UHMWPE fiber has better reinforcing and toughening improvement of concrete.

5. Conclusion
The static mechanical properties and crack-resistance mechanism of steel-UHMWPE HFRC were studied by splitting-tensile and cubic-compression tests. The main conclusions can be given as follows:

(1) Compared with single fiber reinforced concrete, HFRC can better improve the crack resistance properties of concrete at different stages of crack initiation.

(2) The hybrid of UHMWPE fiber and steel fiber has obvious positive effects on the tensile and compressive strength of concrete. Regression analysis showed that the effect of UHMWPE fiber on strength of concrete is better than that of steel fiber.

(3) The enhancement effect of UHMWPE fiber on concrete is obviously better than that of polypropylene fiber compared with the data of conferences, which proves that this kind of high-strength flexible fiber has broad prospects in the application of HFRC.

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