Study on Tensile Properties and Failure Modes of BFRC

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Abstract. The effects of basalt fiber volume fraction and fiber length on the tensile properties of concrete are studied by experiments. The mechanism of fiber improving the tensile failure mode of concrete is analyzed. The results show that the tensile properties of BFRC are significantly improved compared with the matrix concrete. The initial crack strength and yield strength increase significantly with the increase of fiber volume fraction, while the initial crack strain and yield strain increase significantly with the increase of fiber length. The roughness coefficient of BFRC fracture surface can be used as the index of fiber improving concrete tensile properties.

1. Introduction
Fiber reinforced concrete (FRC) is composed of a certain amount of fiber in concrete. The fiber can significantly improve the mechanical properties of matrix concrete. However, compared with the compressive, flexural and durability properties of FRC, the research on the tensile properties of FRC is relatively less. The main reason is that the tensile test of concrete is relatively difficult, and the requirements for specimen production, loading equipment and collection equipment are relatively high. In the past, the research results of FRC tensile test are dispersed, and the regularity of the results is not obvious. With the development of high-performance FRC technology, the aggregate of matrix concrete is mostly fine sand or medium sand. The size of tensile sample can be reduced to 3~4 times of the standard, which can meet the requirements. Therefore, the difficulty of preparation and test of tensile specimen is greatly reduced. At present, the research on the tensile properties of FRC is mainly reflected in the aspects of tensile constitutive relationship and influencing factors analysis. For example, Wille summarized and classified the tensile property test devices, and analyzed the application scope of various types of tensile test devices[1]. At the same time, the uniaxial tensile properties of SFRC with three different volume addition rates were studied, and the strain hardening and tensile softening parameters of SFRC were characterized and analyzed. Combined with the microscopic analysis results, the tensile stress-strain constitutive model of SFRC was proposed. TuYan studied the influence of steel fiber aspect ratio, fiber embedded length and other factors on the tensile properties of the composite[2]. The experimental study of Flávio shows that the influence of fiber shape and interfacial properties on the tensile properties of the composite can not be ignored[3]. Lee evaluated the influence of different fiber inclination angles on the tensile properties of SFRC[4]. The results show that the peak load of SFRC reached the maximum when the fiber inclination angle was 30° and 45°. Based on this, a drawing mechanical model considering fiber inclination angle is
proposed. Li summarized the influence of fiber, matrix and interface between fiber and matrix on the tensile properties of high performance FRC[5].

However, there are few special researches on the tensile properties and failure modes of BFRC. The existing research on the factors affecting the tensile properties of FRC is not deep enough. Therefore, in this paper, the tensile mechanical properties of BFRC with different volume ratio and fiber length are tested and studied, and the laws of basalt fiber improving the tensile properties and failure modes of concrete are analyzed. It provides the basis for the research and development of BFRC materials and engineering application.

2. Test Overview

2.1. Performance of matrix concrete

The strength grade of matrix concrete is C50. Its 28d compressive strength, tensile strength and shear strength are 64.5MPa, 4.7MPa and 4.9MPa respectively. And the tensile ultimate tensile strain is $1 \times 10^{-4}$. The mixture ratio of matrix concrete is shown in Table 1.

| cement | water | sand | stone |
|--------|-------|------|-------|
| 438    | 141   | 1715 | 195   |

Table 1. The mixture ratio of matrix concrete (kg/m³)

The performance index of basalt fiber is shown in Table 2. In this paper, short cut discontinuous fibers with length of 6mm, 9mm, 12mm and 18mm are selected, and the fiber volume blending rate is 0.4%, 0.8%, 1.2% and 1.6%.

| tensile strength /MPa | diameter /(mm) | Elastic modulus /GPa | density /(g/cm³) | length /(mm) |
|-----------------------|----------------|----------------------|-----------------|--------------|
| 3200                  | 0.01           | 100                  | 2.65            | 6, 9, 12, 18 |

Table 2. Fiber performance indicators

2.2 Test procedure

According to the relevant provisions of standard for test methods of fiber reinforced concrete (CECS13:2009), the tensile test was carried out with 8-shaped specimen. The loading equipment is WAW-1000 universal testing machine. The 3D scanner is Handyscan300. The production process of BFRC is shown in figure 1.

Test steps: first, install the tensile fixture and sample to ensure that the sample is free and stable in the vertical direction. And then apply appropriate amount of grease on the connection part between the dowel bar and the fixture steel support. Secondly, the deformation measurement frame and displacement sensor should be installed, and the measurement direction of displacement sensor should be consistent with the loading direction, so as to ensure the objectivity of sample deformation measurement. At the same time, the tensile strain measurement system was installed and debugged to collect the tensile strain on the sample surface, as shown in figure 1. Third, preheat the testing machine for 5 minutes and start pretension. The pretension load is set at 2.5KN. Meanwhile, adjust the sample. Fourth, after the pretensioning, the load, displacement and strain values are returned to zero. And the formal test is carried out. The loading rate is 0.4 MPa/min, and the stress-strain data are collected.

Figure 1. The production process of BFRC
3. Analysis of Test Results

3.1. Analysis of tensile properties of BFRC
The tensile test of BFRC was carried out, the tensile stress-strain curve was collected, and the tensile initial crack point was identified by the method in reference[6]. The arithmetic mean value of the initial crack stress and strain of the four specimens is taken as the initial crack strength and initial crack strain. The variation of initial crack stress and strain with fiber volume fraction and length was analyzed.

![Initial crack strength and strain of BFRC](image)

The variation of initial crack strength and strain of BFRC with different characteristics is shown in figure 2. It can be seen that the initial crack strength of each series of BFRC has a strong sensitivity to the fiber volume addition rate. That is, with the increase of fiber volume addition rate, the initial crack strength of each series of BFRC is significantly improved compared with that of the matrix concrete. When the fiber volume fraction is constant, the influence of fiber length on the initial crack strength of BFRC is relatively little. The results show that the initial crack strain of each series of BFRC increases obviously with the increase of fiber length, and is improved at different levels compared with that of matrix concrete. For example, when the fiber volume fraction is 0.4%, and the fiber length is 18 mm, the BFRC initial crack strain is increased by 69% compared with the matrix concrete. When the fiber length is fixed, the initial crack strain of BFRC has no obvious change with the increase of fiber volume fraction.

The variation of peak strength and yield strain of BFRC with different characteristics is shown in figure 3. According to figure 3, firstly, the tensile yield strength of BFRC increases significantly with the increase of fiber volume fraction. At the same time, the tensile yield strength of BFRC varies with the fiber length, that is, the tensile yield strength of BFRC increases with the increase of fiber length when the fiber volume fraction is constant. The variation of peak strength with fiber length is similar. Secondly, when the fiber length is fixed, the yield strain of BFRC increases in different levels compared with the yield strain of base material concrete, and increases with the increase of fiber volume ratio. For example, when the fiber length is 18 mm and the fiber volume fraction is 1.6%, the yield strain of BFRC is 3.7 times higher than that of matrix. At the same time, the tensile yield strain of BFRC increases with the increase of fiber length when the fiber volume ratio is constant, and it is significantly higher than that of matrix concrete.
In conclusion, the initial crack strength and yield strength of BFRC are more sensitive to the change of fiber volume fraction, while the initial crack strain and yield strain have a strong dependence on the change of fiber length. This conclusion can not only be used as the basis for the design of fiber reinforced concrete materials, but also reflect the obvious difference of fiber volume addition rate and fiber length on the improvement of concrete tensile properties.

3.2. Failure mode analysis of BFRC

The process of concrete tensile failure is essentially a process of energy dissipation and release. Energy dissipation causes damage to concrete materials and leads to deterioration of its internal structure. Energy release is the internal cause of overall fracture instability[7]. According to this, the tensile failure modes of BFRC specimens are analyzed. Figure 4 shows the fracture failure modes of BFRC with different fiber length and fiber volume addition rate. It can be seen from figure 4 that when the fiber volume addition rate is small, the main crack propagation angle (the angle between the crack propagation direction and the sample level) is relatively large, and the overall crack growth length is larger. However, with the increase of fiber volume fraction, the crack propagation angle decreases in varying degrees. The crack propagation path is relatively straight when the specimen is damaged. The mechanism is that when the fiber volume ratio is large, the improvement effect of fiber on concrete is relatively strong, and the weak layer inside the concrete is relatively few. The strain energy accumulation rate is relatively fast and the elastic modulus increases under the action of tension. The energy release rate decreases with the increase of fiber volume fraction, and the number of surface cracks decreases with the increase of fiber volume fraction. Therefore, for the sample with high fiber volume addition rate, the strain energy needs to be released in a short time, forcing the crack to expand along the shortest path of energy release. That is, along the shortest path of horizontal direction (vertical direction of tensile force), and the fracture surface formed follows the principle of maximum energy release.
It can be seen that different types of BFRC tensile specimens show different surface crack roughness. And how to quantitatively describe the crack and fracture surface roughness is the key to analyze the difference of tensile mechanical behavior[8]. In this regard, previous researchers used the roughness coefficient $JRC$ to describe the roughness of failure surface[9-10]. However, the error of $JRC$ acquisition method is large, and it is difficult to be used in the analysis of test results[11]. For fiber reinforced concrete, the tensile mechanical properties of cementitious materials are improved and the crack propagation mode is changed. Therefore, the characteristics of BFRC fracture surface roughness must be related to the geometric characteristics of fiber and the volume addition rate. The analysis law can provide the basis for revealing the mechanism of fiber improving concrete performance. Therefore, the failure surface of BFRC tensile specimen was scanned by Handyscan300 3D scanner, as shown in figure 5(a). The 3D morphology of failure surface of different kinds of BFRC specimens was reconstructed, as shown in figure 5(b). Three dimensional roughness coefficient $R_s$ of failure surface of BFRC tensile specimen is calculated and analyzed, as shown in formula (1)[12].

$$R_s = \frac{A'}{A}$$

(1)

Figure 6 shows the variation of three-dimensional roughness coefficient of BFRC tensile fracture surface with fiber volume fraction. It can be seen that the roughness coefficient of BFRC tensile fracture surface decreases in varying degrees when the basalt fiber volume addition rate varies from 0.4% to 0.8%. For example, when the fiber volume fraction is 0.4%, 0.8%, 1.2% and 1.6%, the tensile fracture surface roughness coefficient of BFRC decreases by 20%~25%, 34%~49%, 49%~60% and 57%~69% respectively compared with that of base concrete. With the increase of fiber volume fraction, the tensile fracture surface roughness coefficient of BFRC shows a significant nonlinear decreasing trend, and it varies with the fiber length. That is to say, the roughness coefficient of BFRC sample with larger fiber length decreases sharply. When the fiber length is fixed, the variation law of BFRC tensile fracture surface roughness coefficient with fiber volume fraction presents a good power function decreasing relationship, as shown in formula (2), and the correlation coefficient is as high as 0.95.

$$R_s = R_0 - 4\left[1 + V_t^{(0.62 - 0.012d_f)}\right]$$

(2)
Where $R_0$ is the tensile fracture surface roughness coefficient of matrix concrete. As an important parameter representing the irregularity and roughness of BFRC tensile fracture surface, roughness coefficient can better characterize the effect of basalt fiber on improving the tensile strength of concrete.

![Figure 6. The change rule of BFRC failure surface roughness coefficient](image)

4. Conclusion
(1) The results show that basalt fiber can improve the initial crack strength and yield strength of matrix in different degrees, and increase with the increase of fiber volume fraction. When the fiber volume fraction is constant, the initial crack strain and yield strain of the composite increase to a certain extent with the increase of fiber length, and increase with the increase of fiber length.

(2) The crack propagation mechanism of different kinds of BFRC is different under tension. With the increase of fiber volume fraction and fiber length, the crack propagation path changes from the principle of minimum energy consumption to the principle of maximum energy release.

(3) The results show that the variation of BFRC tensile fracture surface roughness coefficient with fiber volume fraction shows a good power function decreasing relationship. The decreasing degree increases with the increase of fiber length. The roughness coefficient can be used as an important index to improve the tensile properties of BFRC.

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