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Study on Tensile Stress-Strain Relationship of BFRC

Jingjing He[1*]; Junping Shi[2]; Yong Zhang[1]; Haiting Wang[1]; Haodan Lu[1]; Lihao Fan[1]; Yongtao MIN[1];

[1]Powerchina Xibei Engineering Corporation Limited, Power China, Xi'an, Shaanxi, 710065, China

[2]School of Civil Engineering and Architecture, Xi'an University of Technology, Xi'an, Shaanxi, 710048, China

*Corresponding author's e-mail: hejingji@nwh.cn

Abstract. In this paper, different types of basalt fiber concrete (BFRC) were been researched on the tensile properties. Moreover, analyzed the influence of fiber length and fiber volume fraction on the tensile properties of concrete. The results showed that the tensile strength of BFRC increased significantly with the increase of fiber volume fraction, and the strain increased significantly with the increase of fiber length. The BFRC tensile stress-strain curve shows obvious staged failure, and the function of stress-strain relationship based on the regression method has burning relevance with the test results.

1. Introduction

Concrete materials are recognized as the first-choice material for ideal compression members due to these high compressive strength and small deformation. However, as a kind of quasi-brittle materials, concrete has the disadvantage of low tensile strength, which greatly hinders its application in the engineering fields. Therefore, how to effectively improve the tensile properties of concrete materials has become a topic concern in the industry. For this reason, many scholars in the world have carried out researches on the tensile properties, failure modes and mechanisms of concrete, and obtained a lot of results. For example, Whitney[1] believes that concrete belongs to elastoplastic materials, and there is a descending stage in the tensile stress-strain curve. Hughes and his team[2] learned through experimental researches that when the tensile load reached the maximum, the concrete did not break, but softened, that is, after the stress-strain curve reached the peak, the stress gradually decreased and the strain continued to increase. Li's team[3] improved the tensile connection method of the sample, pasted steel plates at both ends of the concrete tensile specimen, so that the internal tensile stress transmission of the specimen was more continuous and uniform, and according to this method, the uniaxial tensile test of the non-notched specimen obtained relatively ideal results. The research of Cattaneo's group[4] shows that loading method has a greater impact on the concrete axial tensile stress-strain curve. The above scholars analyzed the concrete macroscopic tensile stress state corresponding to each stage of the concrete tensile stress-strain curve, and established the relevant stress-strain relationship, which not only reveals the concrete tensile deformation characteristics and failure modes, but also provides theoretical support for the full-process force analysis of concrete tension members. And a detailed analysis of the factors affecting the tensile properties of concrete can provide a basis for the analysis of the elastic-plastic mechanical behavior, tensile damage and fracture mechanism of concrete members.

However, previous researches were all carried out on ordinary concrete, and relatively few researches on the tensile properties of fiber concrete, and the addition of fibers can significantly improve the mechanical properties of the concrete matrix at various levels. For example, the brittleness of the matrix concrete is significantly reduced, and it exhibits significant ductility characteristics during bending failure and tensile failure. The laws of traditional concrete tensile stress-strain curve relationship and tensile failure can not be applied to fiber concrete. Therefore, it's necessary to conduct a systematic study on the tensile stress-strain relationship and tensile failure law of fiber concrete. In this regard, the tensile mechanical properties of 16 kinds of basalt fiber concrete (BFRC) with different fiber volume fraction and different fiber lengths are studied here, and the influence of fiber volume fraction and fiber length on the tensile stress-strain curve and damage characteristics of BFRC is analyzed.

2. Experimental

2.1 Materials

The cement is 42.5 ordinary Portland cement. The fine aggregate is medium sand, the bulk density is 1555 kg/m^3, the fineness modulus is 2.46, the moisture content is 3.1%, and the mud content is 2.4%. The coarse aggregate is 5 mm~20 mm crushed stone, and the bulk density is 1450 kg/m^3 and the mud content is 0.3%. The water-reducing admixture uses polycarboxylate superplasticizer. Basalt fiber uses short-cut discontinuous fibers with a diameter of 0.01 mm and length of 6 mm, 9 mm, 12 mm, and 18 mm. The strength grade of the matrix concrete is C50, and the mix design is m (cement): m (sand): m (stone): m (water): m (admixture) =1.0:1.46:2.7:0.33:0.02, here the fiber volume fraction is 0.4%, 0.8%, 1.2%, 1.6%.

2.2 Experiment method

Tensile test adopts 8-shaped sample, and the loading equipment adopts WAW-1000 universal testing machine.

Sample preparation: first mix the coarse aggregate sand and stones for 1 minute, then add the cement fiber and mix for 1 minute, and finally add water and mix for 2 minutes, immediately put the mixed fiber concrete into the test mold and vibrate for 30 seconds. 24 hours later, the mold will be disassembled, and the samples will be grouped and numbered, and then enter the maintenance room.

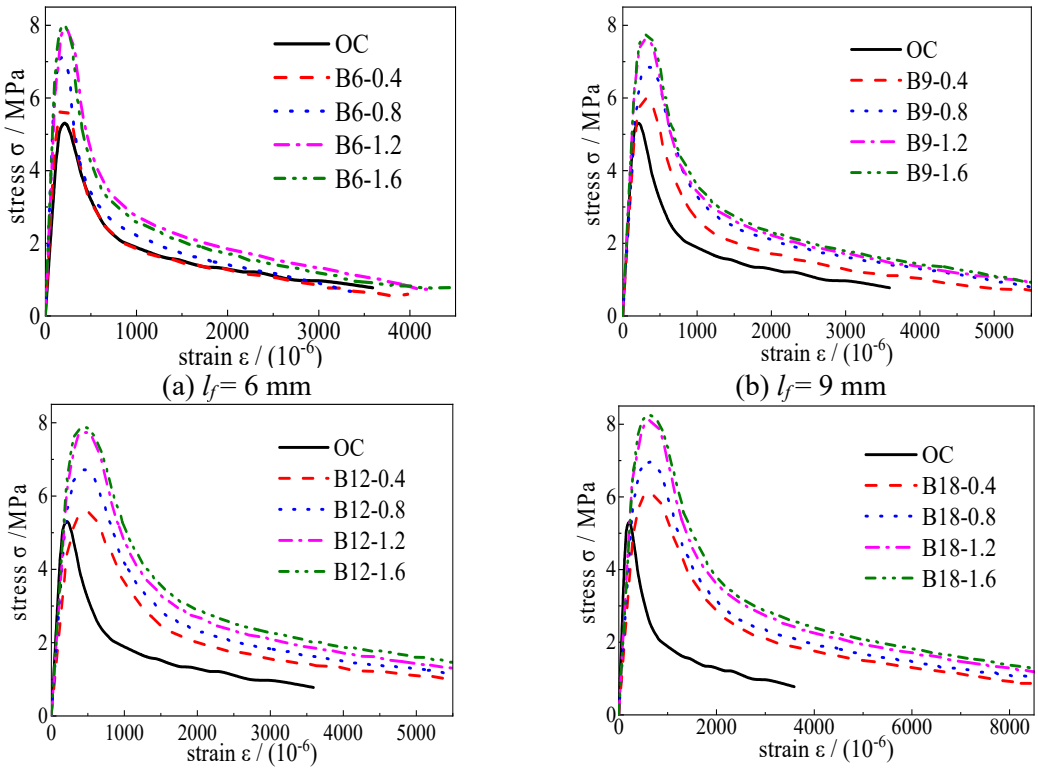
Sample marking: Mark the sample with Bl_f-V_f, l_f represents the length of the fiber, and V_f represents the fiber volume fraction. For example: B6-0.8 represents fiber concrete with a fiber length of 6 mm and a fiber volume fraction of 0.8%, and the matrix concrete is marked as OC. 4 samples are a group, 16 groups of fiber concrete and 1 group of matrix concrete need to be made.

3. Analysis

3.1 The full tensile stress-strain curve

According to the relevant regulations of *Test code for hydraulic concrete (SL 352-2006)*, the tensile test was carried out, the loading rate was 0.4 MPa/min, and collected the load-time, displacement-time, strain-time change data. Take the stress-strain curve of a representative sample in each group as the basis for analysis. Figure 1. shows the tensile stress-strain curves of BFRC with different fiber volume fraction when the fiber length is constant. Combined with the experiment process, the analysis of the curve in Figure 1. found that the form of the full tensile stress-strain curve of each series of BFRC can be roughly divided into five stages, as shown in Figure 2. According to the experiment phenomenon and the damage form, the OA, AB, BC, CD and DE segments of the curve respectively are respectively named linear elastic stage, micro-micro cracking stage, crack stable growth stage, fracture surface formation stage, fiber slip damage stage (fiber pull-out stage). Some scholars call the AB segment of the curve the elastic-plastic yield stage of the material, and collectively call the BCDE segment the softening stage of the material, also called the fracture stage[5]. In short, the division of

each stage of the curve is based on the stress state and damage mode of the sample. For this reason, here is a detailed analysis of the characteristics of each stage of the full tensile stress-strain curve of each series BFRC and fiber improvement mechanism.



(a) l_f= 6 mm (b) l_f= 9 mm

(c) l_f= 6 mm (d) l_f= 9 mm

Figure 1. The tensile stress-strain curve of BFRC

The OA segment mainly appears in the initial stage of load. At this stage, the tensile stress change gradient of the sample tends to a certain value, the stress-strain curve increases linearly, and the unloading of the sample shows that the residual strain is almost zero, and the surface of the sample is also intact. This is because the sample is in an elastic stress state at this stage, the matrix and the fiber are elastically deformed, the fiber and the nearby matrix are basically under the same force, and the relative slip between the fiber and the matrix is zero. That is, the bonding force between the fiber and the matrix is much greater than the overall tensile stress of the sample. If the fiber orientation is not considered, the macroscopic tensile properties of BFRC at this stage conform to the mixing law of composite materials. Therefore, the curve slope of all kinds of BFRC at this stage is greater than that of ordinary concrete, with the increase of fiber volume fraction, it becomes more and more obvious, but the influence of fiber length is less. At this stage, the main function of the fiber is to increase the elastic modulus of the matrix concrete.

The AB segment mainly appears after the curve elasticity stage. At this stage, the stress-strain curve is still linearly increasing, but the stress gradient was significantly smaller than that of OA segment. The unloading law of the specimen shows a certain residual strain. The micro-cracks on the surface of the sample are caused by the fact that the matrix concrete is a heterogeneous material and its internal components have different mechanical properties. At this stage, the fibers are mostly in a state of elastic deformation inside the matrix, and the fiber and the concrete matrix are mostly well bonded. The fiber at the crack tip bears a certain tensile stress, which relieves the stress concentration at the crack tip, thereby the initiation of micro cracks was prevented, and the time of crack aggregation was delayed. This effect varies with fiber length and fiber volume fraction, the specific performance is:

when the fiber length is constant, as the fiber volume fraction increases, the tensile stress of the specimen in the micro-micro cracking stage of the curve is significantly higher than that of ordinary concrete, but the strain has little effect. When the fiber volume fraction is constant, as the fiber length grows, the strain in the curve micro-micro cracking stage increases significantly, but the stress has little effect.

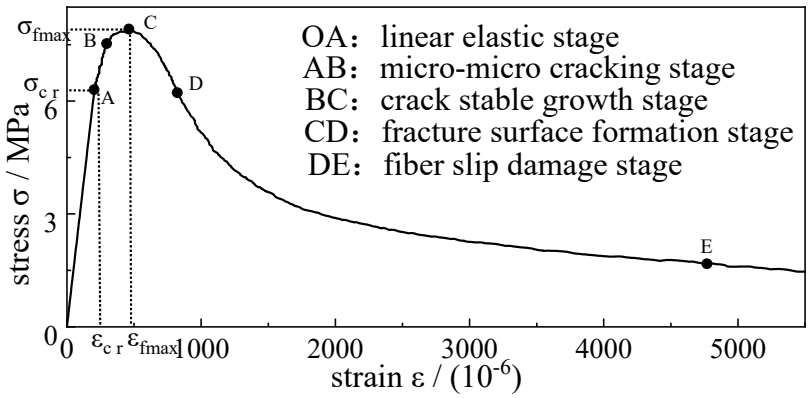


Figure 2. The characterization of BFRC Tensile Stress-Strain Curve

The BC segment mainly appears before the peak stress. At this time, the sample enters the fracture stage, and the stress increases weakly with the increase of strain, showing remarkable nonlinear characteristics. At this stage, one or two main cracks appear on the surface of the sample, which expand steadily as the stress increases, until the stress reaches the peak, and the composite strength fails, and the bridging fiber is pulled out which loses the bond with the matrix. When the fiber does not reach its yield stress, the fiber is subjected to slip stress. The existence of slip stress forces the crack propagation velocity to decrease, thus delaying the main crack propagation and delaying the overall damage of the sample. A large number of fibers in the area outside the main crack are still in a state of good elasticity with the matrix, and the role of the fibers in this area is still to prevent or delay the initiation and convergence of cracks. The above rules are affected by the fiber volume fraction and fiber length, that is: as the fiber volume fraction increases, the stress and strain at the breaking stage of the curve increase. The strength at the peak point (tensile yield strength) was significantly increased with the increase of fiber volume blending rate, which was also affected by fiber length, that is: as the fiber length increases, the yield strength increases within a certain range.

The CD segment appears after the peak stress. At the moment, the sample enters the instable fracture stage. The stress decreases with the increase of strain, the curve shows a convex downward trend, and the stress change gradient is negative, the crack growth rate increases sharply with the increase of strain. At this stage, the surface cracks of the sample accelerate to propagate, and finally a fracture surface is formed, the bridging fiber is pulled out which loses the bond with the substrate. There is still slip stress inside the fiber to inhibit the crack propagation, and some fibers reach their yield stress and are broken. The stress of each series of BFRC increases significantly with the increase of the fiber volume fraction, and the strain increases with the increase of the fiber length. The damage modes of the samples are also different, For example: the damage modes of ordinary concrete samples all show "crack or break", and the fiber concrete series all show the damage form of "apparently severed but actually connected". This phenomenon is more clearly affected by the fiber volume fraction, that is: as the fiber volume fraction increases, the fiber slippage damage takes longer. Therefore, at this stage, the improvement of fiber is mainly reflected in slowing down the instable crack propagation and enhancing the bearing capacity of concrete after cracking.

The DE segment specimen enters the late instable fracture. The stress decreases with the increase of strain, and the curve shows a concave downward trend, as the strain increases, the curve drops gently. The fracture surface of the sample is basically formed, the width of the crack increases with the increase of strain. The failure mode of ordinary concrete specimens is shown as disconnection, while

the fiber concrete series is in the failure mode of "apparently severed but actually connected". The matrix concrete is completely failure, and the stress on the sample is completely borne by the fiber. At the cracks, most of the fibers have slipped failure, the amount of slippage increases with the increase of its strain value, and a few fibers have been broken. The curve characteristics are also affected by fiber volume fraction and fiber length. When the fiber length is constant, the stress and strain of the complex will increase significantly with the increase of the fiber volume fraction. When the fiber volume fraction is certain, with the increase of fiber length, the stress and strain of the complex increased to a certain extent.

3.2 Characteristic analysis of BFRC tensile stress-strain curve

The reasonable acquisition of the stress-strain curve relationship of concrete materials is the key to judging the quality of tensile properties. Since the 20th century, academic circles at home and abroad have conducted a large number of studies on the relationship between the stress-strain curve of concrete. However, most of the studies have been carried out on ordinary concrete. For example, scholars represented by Peterson[6] have obtained a variety of curve relation expressions of different forms through experiments. But there are relatively few studies on the relationship of FRC tensile stress-strain curve. In view of the fact that the mechanical behavior of FRC tensile fracture is different from that of ordinary concrete, for example, there is an obvious fiber slip failure stage during FRC tensile failure, and the tensile strain value is much larger than that of ordinary concrete, showing the failure characteristics of ductile materials. For this reason, here is the expression of the tensile stress-strain curve relationship in different stages of BFRC, and the stress-strain relationship in the OA stage of the defined curve can be a function of zero intercept, as equation (1). Define the stress-strain curve relationship in the AB stage of the curve as a linear function with a non-zero intercept, as equation (2). The stress-strain relationship in BC and CD stages is defined as an exponential function, as shown in equations (3) and (4). The relationship between stress-strain in DE phase is defined as power function, as formula (5).

OA: $$\sigma_f = a_0 \varepsilon_f \qquad 0 < \varepsilon_f < \varepsilon_A \tag{1}$$

AB: $$\begin{cases} \sigma_f = a_1 \varepsilon_f + b_0 & \varepsilon_A \le \varepsilon_f < \varepsilon_B \\ b_0 = (a_0 - a_1)\varepsilon_A \end{cases} \tag{2}$$

BC: $$\sigma_f = a_2 \cdot b_1^{\varepsilon_f} + \sigma_{f\max} \qquad \varepsilon_B \le \varepsilon_f < \varepsilon_C \tag{3}$$

CD: $$\sigma_f = a_3 \cdot e^{b_2 \varepsilon_f} + \sigma_{f\max} \qquad \varepsilon_C \le \varepsilon_f < \varepsilon_D \tag{4}$$

DE: $$\sigma_f = a_4 \cdot \varepsilon_f^{\,b_3} \qquad \varepsilon_D \le \varepsilon_f \tag{5}$$

Among them, ε_A is the strain value at point A, σ_f is the tensile stress, and ε_f is the tensile strain. ε_B is the strain value at point B, and $\sigma_{f\max}$ is the initial crack stress of BFRC. ε_C is the strain value at point C, and a_2 and b_1 are the characteristic coefficients of the curve. ε_D is the strain value at point D, and a_3 and b_2 are curve characteristic coefficients. ε_E is the strain value at point D, and a_4 and b_3 are the characteristic coefficients of the curve. Formulas (1) ~ (5) are used to perform regression analysis on the test data of different types of BFRC stress-strain curves at each stage.

$$\begin{cases} a_0 = (6\times10^{-4} l_f - 0.02)(0.48 l_f + 0.02 V_f) + 0.1 \\ a_1 = 0.67 - (0.01 l_f - 0.3)(0.025 l_f + 0.002 V_f) \\ a_2 = 3.47 l_f - 37.5 V_f - 84.5 \\ a_3 = 1.03\times10^{-4} l_f + 3.35\times10^{-4} V_f - 1\times10^{-5} \\ a_4 = 115.9 l_f + 88.56 V_f - 502.7 \end{cases} \tag{6}$$

$$\begin{cases} b_1 = 0.947 + 0.025\times l_f \\ b_2 = 0.3\times l_f^{-1.5} \\ b_3 = 0.249 - 0.685 l_f - 0.0087 V_f \end{cases} \tag{7}$$

The test data of each stage of the BFRC tensile specimen curve has a higher degree of fit with the proposed function relationship, and the correlation coefficients are all over 0.95. Equation (6) gives the regression analysis results of a_0, a_1, a_2, a_3, a_4 and fiber length and fiber volume fraction, and the correlation coefficients are all over 0.9. The characteristic coefficient b_1 has a significant linear relationship with the change of fiber length, and b_2 has a significant power function relationship with the change of fiber length. The characteristic coefficient b_3 presents a linear polynomial relationship with the change of fiber volume fraction and fiber length, as shown in Equation (7), the correlation coefficients are all over 0.92. So, the staged tensile stress-strain relationship proposed based on the regression analysis method has certain objectivity and can provide a reliable basis for the constitutive relationship analysis of BFRC.

4. Conclusion

BFRC tensile stress-strain curve has obvious stage characteristics, namely: linear elastic stage, micro-micro cracking stage, crack stable growth stage, fracture surface formation stage, fiber slip damage stage and other stages. Based on the regression method, the characteristic relationship of the stress-strain curve of each stage of BFRC is significantly correlated with the experimental data. This conclusion can provide a basis for the study of the constitutive relationship of BFRC. The tensile stress of BFRC increased with the increase of fiber volume fraction, and with the increase of fiber length, the tensile strain of BFRC increased significantly.

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