Experimental Study on Axial Tensile Stress-Strain Relationship of High Crack Resistance Concrete

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Abstract. For demand of high crack resistance of concrete, the calcium-magnesium expansion agents and basalt fiber are chosen. The study of the full stress-strain curve of concrete under uniaxial tensile can comprehensively reflect its mechanical properties. The uniaxial stretch tests are used to study the concrete axial tensile constitutive model, and then the corresponding curve and formula are obtained in this paper. The influence of different dosages and water-binder ratio on the characteristic points of the curve is studied, and a suitable mathematical expression for the axial tensile stress-strain curve is proposed. Studies have shown that by adopting the method of dual admixture of expansive agent and basalt fiber, the toughness, tensile strength, ductility, and even other properties of concrete can be significantly improved. This shows that the dual admixture of the two materials has a strong toughening effect on concrete. With the amount of fiber content, the amount of expansion agent and the water-binder ratio is respectively 1%, 7% and 0.42, the performance of concrete shows the best state. The proposed calculation formula is in good agreement with the experimental results, which can provide a theoretical basis for the design and nonlinear analysis of concrete structures.

Keywords. Expansion agent, basalt fiber, concrete, stress-strain relationship, constitutive equation.

1. Introduction

With the development of the construction industry, people put forward higher requirements on the crack resistance of concrete materials. Presently, there are many researches on the crack resistance of concrete [1]. Most of the researches mainly focus on the influence of fiber, expansion agent and other functional materials on the performance of concrete. However, the tensile strength of concrete is seldom considered in the design of concrete structure. For the crack resistance, it is not enough to simply study its tensile strength. Tensile strength and tensile deformation capacity are both important in the research of crack resistance. Especially when the tensile stress exceeds its ultimate tensile stress, it is necessary to study the development of concrete cracks, the evolution of crack width, the calculation of stress and deformation based on the study of the whole process of concrete axial tensile stress-strain [2].

Xu Libin [3] studied the mechanical properties of basalt and polypropylene hybrid fiber concrete, and carried out axial tensile performance test, then obtained the axial tension constitutive models and curves of different specimens, then determined the constitutive equation. Wang Zhenbo [4] studied the
axial tension and axial compression behavior of hybrid polyvinyl alcohol-steel fiber ductile cement-based materials. Sergio Carmona [5] and others proposed a model in a simple expression for indirectly determining the tensile stress-strain curve of concrete through splitting tensile test based on the experimental results. Zhou Boru [6] studied the influence of steel fiber volume, steel fiber fineness ratio, steel fiber type and active admixtures on the tensile properties of low volume fraction hybrid fiber concrete. L. Li [7] obtained the axial tensile strength and stress-strain relationship of reactive powder concrete through the tensile test, and established the mathematical model of axial tensile stress-strain relationship.

The research on the crack resistance of concrete is mainly focused on the mechanical properties, and there are many limitations. Therefore, through the axial tension test, this paper studies the stress-strain curve of concrete with basalt fiber and calcium magnesium expansive agent, and the constitutive equation is established, which provides reliable and rich theoretical basis and reference research results for the practical application and theoretical research of fiber concrete and provides necessary parameters for calculation.

2. Experiment

2.1. Raw Materials

P·O 42.5 ordinary Portland cement and the fly ash are produced by Nanjing SuBoTe Co. Ltd. Basalt fiber chopped as 12mm are provided by a manufacturer in Wuhan, the properties of which are shown in table 1. The calcium-magnesium expansion agent used in the experiment was provided by a manufacturer in Hebei. The remaining materials are natural river sand and basalt gravel with a particle size of 5-20 mm.

| Diameter (μm) | Length (mm) | Tensile Strength (MPa) | Density (kg/m^3) | Elongation at break (%) | Elastic Modulus (GPa) | Softening Point (℃) | Maximum temperature (℃) |
|--------------|-------------|------------------------|------------------|-------------------------|------------------------|-----------------------|-------------------------|
| 15           | 12          | 4150                   | 2652             | 3.4                     | 100                    | 970                   | 660                     |

2.2. Mixture Ratio Design

Design grade of the concrete is selected as C40. This paper carries out orthogonal experiment with three factors and three levels. The mix ratio scheme is shown in table 2.

| Item | ZL0 | ZL1 | ZL2 | ZL3 | ZL4 | ZL5 | ZL6 | ZL7 | ZL8 | ZL9 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Water| 155.4 | 148 | 148 | 148 | 155.4 | 155.4 | 155.4 | 155.4 | 166.5 | 166.5 | 166.5 |
| EA   | 0 | 18.5 | 25.9 | 33.3 | 18.5 | 25.9 | 33.3 | 18.5 | 25.9 | 33.3 |
| BF   | 0 | 21.2 | 26.5 | 31.8 | 26.5 | 31.8 | 21.2 | 31.8 | 21.2 | 26.5 |

2.3. Experimental Method

The specimen of axial tensile stress-strain test is the prism with the size of 100×100×200 mm. The diameter of rebar is 16 mm, the embedded depth of that is 50 mm and the extension length of that is 100 mm. The loading speed of the test is 0.05-0.08Mpa. Place the displacement meters on both sides of the specimen, and then connect the displacement meters with the DHDAS static stress and strain test data acquisition system to record the concrete deformation data. The stress of concrete is recorded by a universal test machine. The schematic diagram of the device, instrument and test block installation style used in the experiment is shown in figure 1.
3. Results and Discussion

3.1. Cracking Process and Failure Mode of Specimens
In the test, most of the cracks of the specimens are expected to be consistent and basically appear in the middle straight section. When the load is close to the peak value, there will be transverse small but visible cracks. With the increasing of the load, the crack continues to expand and its width also increases. When the load reaches the peak point, the stress is the tensile strength, and the corresponding strain is the peak strain. With the further increase of load, the curve begins to descend, the crack width on the surface increases and extends, then the specimen is suddenly broken. Therefore, the curve of descending section is not ideal. The failure process under axial tension is shown in figure 2.

3.2. Complete Stress-Strain Curve
The axial tensile stress-strain curve of the concrete is shown in figure 3.

Figure 1. Axial tensile stress-strain test device

Figure 2. Process diagram of concrete tensile failure.

Figure 3. Axial tensile stress-strain curves
It can be seen from figure 3 that the trend of these axial tensile stress-strain curves of each group are roughly the same, but the characteristic points on the curve are different. Through the analysis of the curve shape, it can be known that the ductility and peak stress have a greater relationship with the amount of basalt fiber and expansion agent, and the dual mixing of two materials has a significant effect on the performance of concrete. When the two materials of fiber and expansion agent are used in concrete, it can be seen that the change in the rising section of the curve is not obvious, but the slope of the falling section is greatly moderate. As the dosage of fiber increases, the decreasing section gradually slows down, and the strain at the fracture point increases gradually. When the concrete cracks, the fiber can bear part of the tensile stress, which greatly reduces the risk of brittle failure of concrete.

3.3. Analysis of Curve Characteristic Points

3.3.1. Peak Point. The highest point of the axial tensile stress-strain curve is the peak point, which refers to the most direct manifestation of the bearing capacity and deformation capacity of concrete before failure [8]. The greater the stress value at the peak point, the greater the axial tensile strength and the greater the strain corresponding to the peak point, indicating that the greater the plastic strain capacity, the higher the crack resistance. The peak stress and strain of the curve are shown in figures 4 and 5.

![Figure 4. Curve peak stress](image1)

![Figure 5. Curve peak strain](image2)

Analysis of figure 4 shows that except for ZL3, ZL5 and ZL7, the peak stress of other concrete increases significantly. It can be seen that the fiber and expansion agent can significantly improve the strength, thereby achieving the effect of increasing the peak stress of concrete, that is, the maximum tensile strength of concrete can be greatly improved by adding fiber and expansion agent. The peak stress of ZL2 is the highest, which is 34.3% higher than that of ordinary concrete. From figure 5, we can find that the coexistence of the two materials, fiber and expansion agent, also has a very important impact on the peak strain of concrete, which also is the plastic deformation capacity of concrete, indicating that the double addition of fiber and expansion agent has a very significant positive effect on the toughening effect of concrete. The peak strain of ZL3 increases by 15.3% compared with the ordinary concrete. The reason is that the plastic deformation capacity of concrete increases with the increase of fiber dosage, but excessive fiber will lead to the decrease of strength.

3.3.2. Initial Tangent Modulus and Fracture Point. We know that the initial tangent modulus is the slope of the rising section of the curve, which generally is the linear section from the initial point to the elastic limit, that is the initial tensile modulus of elasticity. The smaller the initial modulus is, the better the tensile deformation capacity is. The fracture point is the strain point when the concrete breaks. The greater the strain at the fracture point, the better the ductility and deformation performance of concrete. The initial tensile modulus and strain at the breaking point of each group are shown in the figure 6 and 7.
It can be seen from figure 6 that the initial tensile tangent modulus is affected by the double addition of fiber and expansion agent, but the change range is small. Certainly, double addition of fiber and expansive agent can reduce the initial tensile tangent modulus to improve the elastic deformation performance. However, the concrete is a brittle material, its elastic deformation capacity changes little. It can be seen from figure 7 that the strain at the fracture point is greatly affected by the addition of fiber and expansion agent, which greatly improves the strain value at the fracture point, indicating that the double mixture of fiber and expansion agent has a significant strengthening effect on the ductility.

3.4. Factor Range Analysis
Through range analysis, the influence degree and trend of different influencing factors on different characteristics are discussed. The peak stress, peak strain and the initial tensile tangent modulus are chose for factor range analysis. The results of the range analysis are shown in figure 8.

Analysis of figure 8 shows that with the continuous increase of water binding rate, the stress and strain at the peak and the tensile elastic modulus of concrete gradually decrease. When the amount of expansion agent continues to increase, it can be seen that the stress and strain at the peak increase first and then decrease, and the elastic modulus decreases first and then increases, and the optimum content is 7%. A large number of ettringite crystals and others are generated by hydration of expansive agent, which makes the internal microstructure is more compact and full and then improves the strength, deformation performance and even other properties. However, if the content is too large, the crystal will form a skeleton structure, leaving many pores and reducing the strength. The influences of fiber are similar to those of expansive agent. When the fiber content increases continuously, the strain at the peak of the curve increases greatly, and the elastic modulus gradually decreases, while the stress at the peak of the curve shows a trend of first increasing and then decreasing. Because of the addition of fibers, the plastic deformation ability of concrete has been significantly improved. The peak stress
increases at first and then decreases, and the optimum content is 1%. Because of the specific surface area of fiber, the cement paste to be wrapped is more than that of ordinary concrete. Therefore, when the fiber is excessively mixed, the fiber needs more cement paste to wrap, which requires a large amount of cementing material and water, and in the case of limited cementing material and water, the cement paste cannot completely wrap the fiber and aggregate, which leads to direct contact or exposure of part of the fiber and aggregate, leading to stress concentration and the strength decrease. The analysis above shows that for the influence of the peak stress, peak strain and tensile modulus of elasticity on the curve, the content of basalt fiber is ranked first, followed is the water binder ratio, and the least impact is the amount of expansion agent.

3.5. Determination of Constitutive Equation
Based on the two-stage model of tensile stress-strain curve proposed by the scholar Guo Zhenhai [9], through adjusting the constitutive parameters, the dimensionless stress-strain diagram is fitted. The constitutive equation is as follows. Through curve fitting, the constitutive parameters obtained are shown in table 3.

\[
\text{Ascending section of the curve: } y = \alpha x + (1.5 - 1.25\alpha) x^2 + (0.25\alpha - 0.5) x^6 \quad (1)
\]

\[
\text{Descending segment of the curve: } y = \frac{x}{\beta (x-1)^{\frac{1}{2}} + x} \quad (2)
\]

In equation (1): \(\alpha\) is the parameter of the ascending sections of the curve.
In equation (2): \(\beta\) is the parameter of the descending sections of the curve.

| Item | ZL0 | ZL1 | ZL2 | ZL3 | ZL4 | ZL5 | ZL6 | ZL7 | ZL8 | ZL9 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(\alpha\) | 1.59 | 0.56 | 0.4 | 1.01 | 0.47 | 0.87 | 0.91 | 0.61 | 0.83 | 0.51 |
| \(\beta\) | 0.64 | 0.34 | 0.23 | 0.18 | 0.24 | 0.2 | 0.25 | 0.42 | 0.26 | 0.27 |

4. Conclusion
(1) With the addition of fiber, the tensile strain and the tensile stress increase, and the tensile modulus of elasticity decreases. The strength of the concrete are obviously improved after the calcium-magnesium expansion agent and basalt fiber are added to the concrete. At the same time, the ductility and toughness of concrete have also been greatly improved. The study shows that when the content is 1% and 7%, the effect is the best. In addition, the water binder ratio can reduce the peak stress, peak strain and the tensile modulus of elasticity of concrete.

(2) For the influence of the peak stress, peak strain and tensile modulus of elasticity on the curve, the content of basalt fiber is ranked first, followed is the water binder ratio, and the least impact is the amount of expansion agent.

(3) Through parameter analysis, the parameters of axial tensile stress-strain constitutive equation decrease, which shows that the ascending and descending sections become slower, after adding basalt fiber and calcium magnesium expansive agent. When the content of the two is 1% and 7%, the \(\alpha\) and \(\beta\) of each section are respectively 0.4 and 0.23.

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