Investigation on axial compressive stress-strain relationship of expanded fiber reinforced concrete

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Abstract. In order to improve the crack resistance and durability of concrete, basalt fiber and calcium-magnesium expansion agent was used to test the stress-strain relationship and full curve of axial expansion of fiber-expanded concrete with different factors through three-factor three-level orthogonal test. The study of the influence of structural parameters on the constitutive equation of fiber-expanded concrete with different contents and the relationship between the amount of fibers and expansion agents and the parameters of the constitutive equation of the axial compression stress-strain curve were determined. The results have shown that basalt fibers can significantly improve the toughness and ductility of concrete after failure, and the expansion agents can increase the ductility of concrete. When the fiber content is 1%, the expansion agent content is 7%, and the water-binder ratio is 0.42, the mechanical properties are the best. The constitutive parameter $\alpha$ of the rising section of the axial compressive stress-strain curve is 3.1 and the constitutive parameter $\beta$ of the falling section is 0.6.

1. Introduction

With the construction of large projects such as tunnels, the requirements for crack resistance and durability of concrete materials are becoming higher and higher. The research on the influence of the incorporation of functional materials such as fibers and expansion agents on the performance of concrete has been carried out [1,2]. Among them, basalt fiber has higher tensile strength and elastic modulus, and is a good concrete strengthening and toughening material. Calcium-magnesium expansion agent self-expands due to water reaction, effectively preventing the shrinkage and deformation of concrete. Double-blended fibers and expansion agents can effectively improve the crack resistance of concrete, which is of great significance for improving the durability of concrete.

Perfilov V [3] et al studied the strength and crack resistance of basalt fiber-reinforced concrete and
determined relevant parameters. Zhao Yanru [4] et al studied the stress-strain relationship of the basalt fiber reinforced concrete stress rise section. Wei Hui [5] and others carried out uniaxial compression tests on fiber lightweight aggregate concrete, analyzed the failure process and failure characteristics, and systematically studied the effects of various factors on the peak stress, peak strain and elastic modulus. Dinh N [6] studied the axial compression characteristics of amorphous metal fiber reinforced concrete and proposed the prediction equations of elastic modulus and strain under the peak stress as a function of fiber volume fraction and compressive strength of concrete. Paschal C [7] et al studied the strength of concrete under the condition of high temperature after adding basalt fiber and expanded clay. Huang Kaijian [8] et al used MgO expansion agent to strengthen concrete joints and studied the effects of different dosages on their compressive strength, flexural strength, deformation and micro-cracks. At present, there are many researches on the mechanical properties of basalt fibers and expansion agents [9,10], but less research on double-doped basalt fibers and calcium-magnesium expansion agents, and the research on the constitutive relationship after double-doping is blank. The concrete axial compressive stress-strain full curve is the most basic constitutive relationship of concrete. It is an important physical equation in the analysis of reinforced concrete structures. The study of the concrete axial compressive stress-strain full curve is of great significance for the deep understanding of the mechanical properties of concrete, providing a theoretical basis for the study of cracking properties.

In this paper, through orthogonal experiments, the axial compression stress-strain curve of the expanded fiber concrete is studied. Establish the constitutive equation and determine the parameters of the equation, which provides a theoretical basis for the research of expanded fiber concrete.

2. Experiment

2.1 Experimental materials

The main raw materials of expanded fiber reinforced concrete include the following: P·O 42.5 ordinary Portland cement produced by a cement company in Nanjing; grade I fly ash produced by a company in Nanjing; basalt gravel filled 5~30mm; natural river sand with a fineness modulus of 2.56; 12mm chopped basalt fiber produced by a company in Shanghai (its mechanical properties are shown in Table 1); calcium magnesium expansion agent produced by a company in Shandong (its chemical composition is shown in Table 2); polycarboxylic acid type superplasticizer with a water reduction rate of 30-40%.

| Table 1. Mechanical properties of basalt fiber. |
|-----------------------------------------------|
| Material | Length /mm | Diameter /μm | Density / (kg/m³) | Tensile Strength /MPa | Elastic Modulus /GPa | Elongation at break /% | Maximum temperature /℃ | Softening Point |
| BF       | 12         | 16           | 2650             | 4150                 | 100                  | 3.2                      | 650               | 960           |

| Table 2. Chemical composition of expansion agent (%). |
|-----------------------------------------------|
| Material | MgO | CaO | SiO₂ | Al₂O₃ | Fe₂O₃ | L.O.I | Σ |
| EA       | 49.09 | 40.06 | 6.34 | 0.91 | 1.24 | 1.35 | 99.98 |
2.2 Mix ratio design

Based on C40 ordinary concrete mix ratio, double-mix fiber and expansion agent. Three factors and three levels of orthogonal tests are used. The orthogonal test factor levels and the concrete mix of each group are shown in Tables 3 and 4.

**Table 3. Orthogonal test factor level table.**

| Level | A (W/B) | B (EA) | C (BF) |
|-------|---------|--------|--------|
| 1     | 0.4     | 5%     | 0.8%   |
| 2     | 0.42    | 7%     | 1%     |
| 3     | 0.45    | 9%     | 1.2%   |

**Table 4. Composite concrete material mix ratio (kg.m⁻³).**

| No. | XP0 | XP1 | XP2 | XP3 | XP4 | XP5 | XP6 | XP7 | XP8 | XP9 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Water | 155.4 | 148 | 148 | 148 | 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 methods

Axial compression test of concrete is carried out in accordance with GB / T50081-2011 "Standard for Test Methods of Mechanical Properties of Concrete". The test pieces used 100 × 100 × 300mm prisms, and were placed in standard conservation environment for 28 days.

Load at a speed of 0.05-0.08MPa/s, accurate to 0.1MPa. Attach a strain gauge vertically to the middle of the test piece and connect to the DHDAS static strain test system. Load sensors, test pieces and pads were placed on the 2000kN press working platform, and displacement gauges were placed on both sides of the test piece. The displacement gauge was connected to the DHDAS static strain test system. The schematic diagram of the test device is shown in Fig.1.

Before the test, start the press to preload at about 40% of the breaking load, use the strain gauge readings for physical alignment adjustment and compression stability adjustment, until the difference between both strain gauge readings is ≤15%, and the average value of two strain gauges is close. If the readings are too different, you need to adjust the position of the test piece and the load transfer device. After adjustment, pre-press again until the alignment is completed. After starting the formal loading, the loading should be kept continuous until the surface of the specimen is penetrated by cracks.

![Fig.1 Schematic diagram of axial compression stress strain test device.](image-url)
3. Results and discussion

3.1 Stress-strain curve

Each group of tests takes 3-5 test blocks. The axial compression stress-strain relationship curve of each group of concrete and its dimensionless relationship curve are shown in Fig.2 and Fig.3.

![Fig.2 Axial Compression stress-strain curves.](image1)
![Fig.3 Dimensionless curve.](image2)

It can be seen from Fig.2 and Fig.3 that the stress-strain curves of the concrete of each group are basically similar, but different amounts of fibers and expansion agents have different effects on their ductility and peak stress. The proportion limit of ordinary concrete is 40% - 50% of the peak stress, and the proportion limit of expanded fiber concrete is about 70% of the peak stress. The value of this test curve failure ultimate strain is between 0.0025 and 0.0035.

3.2 Curve characteristic point analysis

3.2.1 Peak point and modulus. The peak point of the concrete stress-strain curve is the most intuitive manifestation of the bearing and deformation of concrete before failure. Concrete modulus is the initial tangent modulus and the peak secant modulus on the stress-strain curve. The larger the value, the greater the toughness of the concrete in the same strain interval, and the greater the energy absorbed. The modulus and peak point stress and strain of each group of concrete are shown in Fig.4 and Fig.5.

![Fig.4 Peak point stress and strain of each group of concrete.](image3)
![Fig.5 modulus of each group of concrete](image4)

It can be seen from Fig.4 that, except for XP3, XP5, XP7, the peak axial pressure points of concrete have significantly increased. Fibers and expansion agents have significantly improved the peak axial strength and strain. XP2 had the highest peak point, increasing by 19.52% compared with ordinary concrete. The change trend of stress and strain at the peak point is similar but not completely consistent.

It can be seen from Fig.5 that the fibers and the expansion agent also have effects on the initial
tangent modulus and peak secant modulus of the concrete. XP2 had the highest initial tangent modulus and peak secant modulus, which increased by 17.28% and 14.93% respectively. The change law of initial tangent modulus and peak secant modulus is the same.

3.2.2 Inflection point and critical shear point. The inflection point is the point where the second derivative of the descending section of the stress-strain curve is zero. When the inflection point appears, the larger the residual stress and the cumulative strain, the gentler the rapid decline of the stress after the peak, the better the ductility of concrete. The critical shear point is the point where the third derivative of the descending section of the concrete stress-strain curve is zero. Generally, the residual stress and cumulative strain at the full shear critical shear point of fiber-reinforced concrete are improved compared to ordinary concrete [11]. The stresses and strains at the critical shear point and the inflection point of each group of concrete are shown in Fig.6 and Fig.7.

It can be seen from Fig.6 and Fig.7 that the fibers and the expansion agent have an effect on improving the stress and strain at the inflection point and the critical shear point, having a significant enhancement of ductility. The stress at the two points of XP2 was the largest, which increased by 15.2% and 31.67% respectively compared with ordinary concrete. In addition, the trend of stress-strain changes at the inflection point and critical shear point is the same as the peak point.

![Fig.6 Stress and strain at the inversion point](image1)

![Fig.7 Stress and strain at critical shear point](image2)

3.3 Orthogonal range analysis

Through the range analysis, explore the influence mechanism of different factors on different characteristics. The trend of stress-strain change at the inflection point and critical shear point is the same as the peak point, and the change rule of peak secant modulus and initial tangent modulus is also the same. Therefore, the peak point stress, strain and initial tangent modulus are selected for range analysis. The results are shown in Fig.8.

It can be seen from Fig.8 that as the w/b increases, the peak stress and elastic modulus gradually decrease, and the strain increases first and then decreases. Because the increase of w/b reduces the strength and elastic modulus of concrete. With the increase of expansion agent, the strain increases, so the expansion agent can improve the ductility of concrete. The peak stress and elastic modulus increase first and then decrease, and the best is when the content is 7%. Because expansion agent participates in hydration, generates lots of ettringite crystals, makes the
internal structure more compact and increases the strength of the concrete. If the amount is too large, many pores will be left in the skeleton structure formed by this crystal, thereby reducing the strength and elastic modulus of the concrete. The effect of fiber on it is similar to that of the expansion agent. With the increase of fiber content, the strain gradually increases, and the fiber can greatly improve the ductility of concrete. The peak stress and elastic modulus first increase and then decrease, and the best is when the content is 1%. This is because the fiber has a large specific surface area and requires more cement paste to be wrapped. When the fiber content is too large, the limited cement paste cannot effectively wrap the fibers and aggregates. There is no cement stone connection between the fibers, which leads to stress concentration in these places, and the strength and elastic modulus are greatly reduced. It can be known from the range analysis that the fiber has the greatest influence on the peak stress, strain, and elastic modulus, followed by the w/b.

3.4 Constitutive equation

According to the concrete stress-strain constitutive equation proposed by Guo Zhenhai [12], the dimensionless stress-strain diagrams were fitted by adjusting the constitutive parameters. The constitutive parameters of each group of concrete after curve fitting are shown in Table 5.

\[
\text{Ascent section: } y = \alpha x + (3 - 2\alpha)x^2 + (\alpha - 2)x^3
\]
\[
\text{Descending section: } y = \frac{x}{\beta (x-1)^2 + x}
\]

In the formula: \(\alpha\) and \(\beta\) are the parameters of the rising and falling segments of the curve, respectively.

| No. | XP0 | XP1 | XP2 | XP3 | XP4 | XP5 | XP6 | XP7 | XP8 | XP9 |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \(\alpha\) | 2.81 | 3.05 | 3.1 | 2.74 | 3.02 | 2.78 | 2.86 | 2.77 | 3.03 | 3.04 |
| \(\beta\)  | 0.65 | 0.62 | 0.6 | 0.85 | 0.55 | 0.8  | 0.68 | 0.93 | 0.58 | 0.59 |

\(\alpha\) and \(\beta\) are the parameters of the constitutive equation, and their numerical values directly determine the trend of the curve, and they can also reflect the toughness of the concrete before failure and the ductility after failure. The change of \(\alpha\) corresponds to the initial tangent modulus. The larger the value, the better the toughness of the concrete. The change in \(\beta\) is opposite to the change in stress at the critical shear point. The smaller the value, the better the ductility of the concrete. The use of basalt fiber and expansion agent double-mixing technology can effectively improve the toughness and ductility of concrete and reduce the brittleness of concrete. However, if the amount is too large, the opposite effect will occur. Fibers and expansion agents are best when blended at 1% and 7%.

4. Conclusions

(1) A proper amount of basalt fiber can effectively improve the strength, toughness and ductility of concrete. After the fiber is added, the stress, the strain and elastic modulus of each characteristic point on the stress-strain curve of the concrete are improved. Expansion agents also have a certain effect on improving the strength, toughness and ductility of concrete. The double doping effect is the best, the best is when the dosage is 1% and 7% respectively. Increasing of the w/b reduces the peak
stress, strain and elastic modulus of concrete.

(2) Basalt fiber has the greatest influence on the peak stress, strain, and elastic modulus of the concrete stress-strain curve, followed by the w/b, and finally the calcium-magnesium expansion agent.

(3) After double mixing basalt fiber and expansion agent, the parameters of the rising section of the concrete's axial compressive stress-strain curve increased, and the parameters of the falling section decreased. It shows that the toughness and ductility of concrete have improved. When the blending amounts are 1% and 7%, the ascending section and the descending section are 3.4 and 0.6 respectively.

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