Experimental Study and Analysis on Compressive and Tensile Behavior of Basalt Fibre Reinforced Concrete

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Abstract. Blending a certain proportion of basalt fiber into concrete improves the toughness of concrete, which enhances the tenacity and prevents cracking, thus avoiding the brittle behaviors of concrete. In this paper, the compressive and tensile tests of the concrete with different basalt fiber contents were carried out. Then, the test phenomena, failure modes, and mechanical properties were compared and analyzed to derive the relationship between the basalt fiber contents and the mechanical properties. The results showed that the improvement effect of the basalt fiber on the compressive strength of concrete was lower than that of tensile strength. When the basalt fiber content is 0.3% and 0.4%, the improvement effect was the highest. In the meanwhile, the correlation coefficient of the fiber physical and mechanical parameters and content was introduced to establish the calculation formula for the crack width of basalt fiber reinforced concrete. Finally, the toughness and crack resistance performance of basalt fiber concrete were evaluated by the fracture energy and characteristic length proposed by Hillerborg. The results showed that basalt fiber can significantly improve the toughness and crack resistance performance of concrete.

1. Introduction

As an excellent building material, concrete has the advantages of high compressive strength, excellent corrosion resistance and low price. It is still the most widely used building material in the world. However, as an artificial brittle material, concrete is relatively poor in terms of tensile strength, bending resistance, impact resistance and toughness. As the service time increases, the defects of concrete become increasingly prominent, which leads to many problems in engineering applications.

At present, in order to overcome the defects of concrete, it is internationally recognized that fibres may be added to concrete. In the past two decades, blending fibres into concrete has been widely applied in some projects [1-6], such as railway sleepers, dams, and airport sidewalks. Researchers had also investigated the fibre concrete by blending it with polypropylene fibre, polyvinyl alcohol fibre, steel fibre, glass fibre, and carbon fibre in order to improve the tensile strength, bending resistance and impact resistance of concrete, thus enhancing the toughness and preventing cracks [7-11]. However, there is relatively little research on the basalt fibre concrete.

Basalt fibre has significantly different characteristics from other high-tech fibres [12-16]. The raw material for basalt fibre originates from natural volcanic rock, which has high chemical and thermal stability but does not produce any harmful gas or waste residue in the fibre production process. It is a new green material that meets the requirements of environmental protection; the strength of basalt fibre is much higher than that of natural fibre and synthetic fibre. In addition, its elastic modulus is similar to that of carbon fibre, both higher than that of other fibres, while their comprehensive performance is
equivalent, but the cost of basalt fibre is lower than one-tenth of carbon fibre. In addition, as a multifunctional fibre, basalt fibre possesses comprehensive and excellent quality: acidic and alkaline resistance, low and high temperature resistance, and excellent wettability. Due to its three-dimensional molecules, compared with one-dimensional linear polymer fibres, it has higher compressive strength and shear strength; it has excellent suitability and aging resistance in harsh environments. Related research results showed that basalt fibre can play an important role in enhancing the toughness and preventing cracks in concrete, mainly in the following three aspects [17-24]. Due to its high elastic modulus and tensile strength, basalt fibre reinforces the concrete in a microscopic perspective and acts as a bridge at the cracks. It can inhibit crack propagation, increase the energy absorption capacity of concrete and improve the toughness of concrete. As an inorganic material, basalt fibre has high interfacial bonding strength with concrete. Basalt fibre is excellently dispersed in concrete, while fibres and concrete are exceptionally combined, which increases the reinforcement effect of fibre reinforced concrete and limits the pulling ability of fibres. However, due to the physical and mechanical properties of fibres, there is a certain difference in the optimal basalt fibre contents. In addition, there is a lack of related toughness evaluation index, resulting in the difference in test results.

In this paper, the basalt fibre content was adopted as a single variable and the influence of basalt fibre content on the mechanical properties of concrete was studied. The optimal basalt fibre content was obtained. Combined with the existing toughness evaluation methods, a unified toughness evaluation method was proposed; compared with the calculation method for the crack width of ordinary concrete, the physical quantity related to fibre was introduced, and the calculation formula suitable for the crack width of basalt fibre reinforced concrete was established.

2. Experiments

2.1. Specimens Preparing

Two kinds of specimens were designed for compression test (150 mm × 150 mm × 150 mm) and tensile test (150 mm × 150 mm × 550 mm). The volume content of BFRP were selected as 0%, 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%. The samples were divided into seven groups, numbered B0, B1, B2, B3, B4, B5 and B6, respectively. Three specimens were selected for each group of repeated tests, namely 42 specimens.

For the tensile test of concrete, the two ends of the specimen were pre-embedded with rebar (20 mm in diameter, 125 mm in buried depth, 50 mm in exposed nail length) according to GB/T 50081-2002 “Standard for test method of mechanical properties on ordinary concrete” [25] and CECS 13-2009 “Test method for steel fibre reinforced concrete” [26]. In order to prevent producing stress concentration near the embedded bar, the embedded part was tied with claw type vacuum wires above the front, as shown in figure 1.

![Figure 1. Specimen of tensile test.](image)

According to JGJ/T 221-2010 “Technical specification for application of fibre reinforced concrete”, we selected P·O 42.5 Portland Cement, the sand from the river in Mianyang whose modulus of fineness was about 2.5 (sand ratio 30%), local ordinary gravel stones (16 to 20 mm), and the local tap water. The water-cement ratio of cast-in-place concrete was 0.42, and the collapse degree is 30-50 mm. according to the SL677-2014 “Specification for Hydraulic Concrete Construction”. The concrete’s mixture ratio was shown in table 1, the specific parameters of BFRP were shown in table 2.
The preparation, pouring and curing of concrete specimens were in accordance with GB/T 50080-2016 “Standards for Test Method of Performance on Ordinary Fresh Concrete” [27] and CECS 13-2009 “Standard Test Method for Steel Fibre concrete” [26]. A forced mixer was used to mix BFRC. The secondary mixing method was adopted to avoid fibre agglomeration. First, fine aggregate and BFRP were mixed dryly for 30 s until they were evenly mixed, and then coarse aggregate, cement and water were put in. All materials were stirred for 280 s after putting in. Vibro-compaction moulding technology was used to pour concrete into the moulds for moulding. After 24 hours, the specimens were removed into the Standard Curing Room for curing.

| Component     | Mixture ratio |
|---------------|---------------|
| Cement (kg/m³)| 330           |
| Stone (kg/m³) | 1389.6        |
| Sand (kg/m³)  | 540.5         |
| Water (kg/m³) | 139           |

Table 2. Related parameters of BFRP.

| Name            | BFRP            |
|-----------------|-----------------|
| Type            | Short-cut       |
| Diameter (µm)   | 15              |
| Length (mm)     | 12              |
| Density (g/cm³) | 2.65            |
| Tensile strength (MPa) | 3500-4500 |
| Elasticity modulus (GPa) | 95-115  |
| Extension at break (%) | 2.4-3.0    |

2.2. Loading Test
According to GB/T 50081-2002 “Standards for Test Method of Mechanical Properties on Ordinary Concrete” [25] and CECS 13-2009 “Standard Test Methods for Steel Fibre Concrete” [26], loading rates of compressive, tensile and bending tests were 11.25kN/s and 0.04mm/min, respectively. Loading images were shown in figure 2.

![Loading images](image)
In the tensile test, the main difficulty is the axis alignment of specimen clamping. Therefore, the pre-embedded bars at the end of the test piece were connected to the load testing machine through the Spherical Plain Bearing, as shown in figure 3. Since the spherical plain bearing was made of high-strength steel, it can rotate freely, ensuring the axial alignment of the stressed specimens. In terms of test measurement, the Block Clips (figure 3) were designed on both sides of the specimen for installing two LVDTs to measure the displacement. Two strain gauges (100mm×3mm) were attached to the side of the specimen to monitor the surface cracking of the specimen and find the initial crack point of the specimen. The strain of the specimen was taken as the average of strain value on two opposite sides.

3. Failure Mode

3.1. Compressing Failure Mode

With the increase of load, the plain concrete specimen (B0) was crushed with a loud noise finally. Because of the cyclo-hoop effect, surrounding concrete was crushed and spalled after maximum load, and concrete block was pyramidal, as shown in figure 4.

For the BFRC (B1, B2, B3, B4, B5 and B6), the crack width increased gradually after cracking with debris fell. The cross sectional area showed an external drum shape. However, the specimens cracked but not broken. Their destruction was not as sudden and quick as that of B0. The first sound of destruction was noisy and tearing and finally destruction was followed by a dull sound (figure 4).

Figure 3. Spherical plain bearing and block clips.

Figure 4. Tensile failure mode.
3.2. Tensile Failure Mode
For the plain concrete specimen (B0), the load increased steadily along with the increase of displacement in the early stage of the test. When the deformation was close to the ultimate displacement, the increase amplitude of the load value had no obvious change. When macroscopic cracks appeared in the middle of the specimen, the specimen broke into two sections, the cracking process was extremely fast and the section was smooth and clear (figure 5).

![Figure 5. Plain concrete.](image)

For the BFRC (B1, B2, B3, B4, B5, B6), the load increased linearly with the increase of displacement at the initial stage of loading. When the deformation approached the ultimate displacement, the growth rate of the load slowed down. When macroscopic cracks were observed in the middle of the specimen, the specimen was broken into two sections with clear but uneven fracture. Similar to the case of plain concrete, the fracture sound of BFRC was smaller and there were a lot of tensional fibres in the fracture surface. Because the elastic modulus of BFRP was too low to bear the load effectively, the tensile load was close to zero. The specimen continued to be stretched, the fibres at the fracture were observed to be pulled off after the fracture, which indicated that BFRP had a fine bond performance with concrete (figure 6).

![Figure 6. BFRC.](image)

4. Performance Parameters of Compressing
Through compressing test, the mechanical properties parameters of BFRC can be obtained as shown in table 3 and figure 7.

![Figure 7. Compressive test curve.](image)
Table 3. Performance parameters of specimens.

| Specimen | B0 | B1 | B2 | B3 | B4 | B5 | B6 |
|----------|----|----|----|----|----|----|----|
| $V_f$ (%)| 0  | 0.1| 0.2| 0.3| 0.4| 0.5| 0.6|
| $f_c$ (MPa)| 39.24| 39.98| 40.12| 41.23| 41.08| 39.1| 38.23|
| $\lambda_c$ (%)| 0.00| 1.89| 2.24| 5.07| 4.69| -0.36| -2.57|
| $\delta_c$ (mm)| 1.38| 1.81| 1.79| 2.55| 2.4| 2.22| 1.91|
| $I_0$ | 3.51| 4.07| 4.3| 4.7| 4.74| 3.95| 3.79|
| $I_1$ | 5.66| 7.35| 7.49| 8.64| 8.52| 7.15| 7.13|

where $V_f$ is the volume content of BFRP; $f_c$ is compressive strength; $\lambda_c$ is increasing rate of compressive strength; $\delta_c$ is the peak displacement; $I_0$ and $I_1$ are toughness index.

According to the test results and the study on the properties of FRC concrete or FRP reinforced mortar, this paper carried out linear regression in range of the volume content from 0% to 0.4%.

4.1. Compressive Strength

The quantitative relationship between compressive strength and the volume content were obtained in figure 8.

![Figure 8. Relationship between volume content and compressive strength.](image)

The relationship between compressive strength and volume content of BFRC was given by

$$f_c = 4.98V_f + f'_c \ (R^2 = 0.8549)$$  \hspace{1cm} (1)

where $f'_c$ is compressive strength of the plain concrete.

It can be seen from equation (1) that there was a poor agreement with fitted curve and experiment data. The results show that the compressive strength of concrete has not been significantly improved by the incorporation of BFRP.

4.2. Evaluation of Compressive Toughness

Considering the stiffness of the testing machine and the test errors, the compressive toughness were evaluated by the toughness index.

The ductility of concrete is the ability to maintain deformation after cracking, that is, the area enclosed by the load-displacement curve and x-coordinate. Combined with the methods of ASTM-C1080 and JSCE-SF4, an advanced toughness evaluation method was proposed in this paper. The peak deflection of 0.5, 1.0 and 1.5 times was selected as the reference deflection, i.e. $0.5\delta_c, \delta_c, 1.5\delta_c$. Accordingly, the toughness was evaluated by the area of $A_1, A_2$ and $A_3$, as shown in figure 9; the
toughness was represented by $I_0$ and $I_1$, see equations (2) and (3). In addition, the specimen had been damaged and had basically lost its bearing capacity under the larger axial displacement. Therefore, there was no significance to make the further analysis and discussion here.

The results (table 3) showed that BFRP can significantly improve the toughness of concrete. At first, the toughness index of concrete increased, then decreased with the increase of volume content. When the volume content was 0.4%, the toughness index $I_0$ reached maximum; the volume content was 0.3%, the toughness index $I_1$ was the largest.

The relationship between volume fraction and toughness index was shown in figures 10 and 11.

The relationship between toughness index and volume content was expressed as

$$I_0 = 3.155V_f + I_0' \quad (R^2 = 0.9556) \quad (4)$$

$$I_1 = 12.728V_f - 13.367V_f^2 + I_1' \quad (R^2 = 0.9877) \quad (5)$$
where $I_0', I_1'$ is toughness index of the plain concrete.

According to the equations (4) and (5) and figure 11, the toughness of BFRC increased linearly with the increase of volume content before cracking. After cracking, toughness of BFRC gradually reached the critical volume content, then the growth slowed down slightly.

5. Tensile Performance Parameters
Through the tensile test of BFRC, the full tensile stress-strain curve of BFRC was showed in figure 12 and the tensile performance parameters were given in table 4.

![Figure 12. The tensile stress-strain curve.](image)

**Table 4. Tensile performance parameters.**

| Specimen | B0  | B1  | B2  | B3  | B4  | B5  | B6  |
|----------|-----|-----|-----|-----|-----|-----|-----|
| $V_f$    | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 |
| $f_t$ (MPa) | 3.48 | 3.6 | 3.88 | 4.16 | 4.21 | 3.54 | 3.36 |
| $\lambda_t$ (%) | 0.00 | 3.45 | 11.49 | 19.54 | 20.98 | 1.72 | -3.45 |
| $E_t$ (GPa) | 18.3 | 18.1 | 18.7 | 19.4 | 19.1 | 19.3 | 17.9 |
| $\lambda_E$ (%) | 0.00 | -1.09 | 2.19 | 6.01 | 4.37 | 5.46 | -2.19 |
| $\varepsilon_t$ (με) | 181.02 | 185.43 | 198.75 | 212.32 | 223.57 | 201.02 | 184.50 |
| $\lambda_E$ (%) | 0.00 | 2.44 | 9.80 | 17.29 | 23.51 | 11.05 | 1.92 |
| $\omega_f$ (mm) | 0.226 | 0.243 | 0.267 | 0.275 | 0.311 | 0.249 | 0.229 |
| $\lambda_{\omega}$ (%) | 0.00 | 7.52 | 18.14 | 21.68 | 37.61 | 10.18 | 1.33 |
| $G_f$ (N/m) | 162.3 | 168.45 | 197.1 | 220.8 | 232.05 | 223.35 | 182.7 |
| $\lambda_{G}$ (%) | 0.00 | 3.79 | 21.44 | 36.04 | 42.98 | 37.62 | 12.57 |
| $L_{ch}$ (mm) | 245.25 | 282.31 | 293.80 | 297.03 | 300.08 | 257.99 | 231.74 |
| $\lambda_{L}$ (%) | 0.00 | 15.11 | 19.79 | 21.11 | 22.36 | 5.19 | -5.51 |

where $f_t$ is the tensile strength, $\lambda_t$ is the increasing rate of tensile strength, $E_t$ is the tensile elastic modulus, $\lambda_E$ is the increasing rate of elastic modulus, $\varepsilon_t$ is the ultimate tensile strain, $\lambda_E$ is the increasing rate of ultimate tensile strain, $\omega_f$ is the maximum crack width, $\lambda_{\omega}$ is the increasing rate of crack width, $G_f$
is the fracture energy, $\lambda_G$ is the increasing rate of fracture energy; $L_{ch}$ is the characteristic length, $\lambda_L$ is the increasing rate of characteristic length.

As seen in table 4, the volume content of BFRP had a great influence on the tensile strength of concrete. With the increase of volume content, the tensile strength firstly increased and then decreased. When the volume content was 0.4\%, the tensile strength was increased most (4.21\%), the tensile elastic modulus, ultimate tensile strain and maximum crack width were increased by 4.21\%, 4.37\%, 23.51\% and 37.61\% respectively. However, when the volume content was 0.5\% and 0.6\%, the tensile strength decreased instantaneously. The specific reason was that the dispersion of BFRP was too worse to result in the weak area inside concrete. In conclusion, BFRC had good toughness and crack resistance performance when the volume content was 0.4\%.

As was stated above, this paper only carried out linear regression in the range of volume content from 0\% to 0.4\% and obtained the relationship between the volume content of BFRP and tensile strength, ultimate tensile strain, crack width, fracture energy, characteristic length.

5.1. Tensile Strength and Ultimate Tensile Strain
The relationship between tensile strength, ultimate tensile strain and volume content of BFRP were drawn based on the test results (figures 13 and 14, equations (6) and (7)).

$$f_t = 2.15V_f + f_t' \quad (R^2 = 0.9575) \quad (6)$$
$$\varepsilon_t = 114.79V_f + \varepsilon_t' \quad (R^2 = 0.9719) \quad (7)$$

where $f_t'$ is tensile strength of the plain concrete; $\varepsilon_t'$ is ultimate tensile strain of the plain concrete.

Figures 8 and 13 showed that the incorporation of BFRP can significantly improve the tensile strength of concrete. In addition, the effect of volume content on compressive strength was less than that of volume content on tensile strength. In general, when the volume content of BFRP is 0.3\%, the compressive strength of concrete increased by 5.07\%. When the volume content of BFRP was 0.4\%, the tensile strength of concrete increased by 20.98\%.

For the result of relationship between elasticity modulus and volume content, it is found that the correlation coefficient was not satisfactory ($R^2=0.6739$). Therefore, the regression equation was not listed and the specific relationship needs to be further studied.

5.2. Crack Width
In the tensile process of BFRC, the total deformation $\delta$:
$$\delta = \delta_e + \delta_0 + \omega \quad (8)$$
\[ \delta_e = \frac{\sigma_p}{E_t} l \]  
(9)

\[ \delta_0 = \delta_p - \delta_e \]  
(10)

where \( \omega \) is the crack expansion width (mm); \( \delta_e \) and \( \delta_0 \) is the elastic deformation and residual deformation (mm); \( \sigma_p \) is the peak stress (MPa); \( l \) is the gauge length of the specimen (mm); \( \delta_p \) is the peak stress corresponding deformation (mm).

The crack width and gauge length of the specimen were irrelevant, meanwhile there were no macroscopic cracks before peak stress. From Eq.8, the crack expansion width can be expressed:

\[ \omega = \delta - \delta_e - \delta_0 \]  
(11)

Then, the relative stress-crack width curve (figure 15) and the new fitting equation (13) were obtained according to equations (11) and (12).

Figure 15. Relationship between \( \sigma_r \) and \( \omega_r \).

The empirical equation derived by scholars [28] was as follows:

\[ \sigma = f_t \{ 1 - \varphi \exp \left[ -\left( \frac{\omega}{\omega_f} \right)^n \right] \} \]  
(12)

With the method of fitting regression, the new expression was obtained:

\[ \sigma_r = \alpha - (\alpha - \beta) \exp \left[ -(k \omega_r)^n \right] \]  
(13)

\[ \sigma_r = \frac{\sigma}{f_t} \]  
(14)

\[ \omega_r = \frac{\omega}{\omega_f} \]  
(15)

where \( \sigma_r \) is the relative tensile strain; \( \omega_r \) is the relative crack width; \( \alpha = 0.0418, \beta = 1.3082, k = 11.7864, n = 0.4932 \), \( \alpha, \beta, k, n \) were all related to the type, aspect ratio, density, other physical and mechanical parameters of BFRP. Among them, \( R^2 = 0.9784 \).

5.3. Maximum Crack Width

According to the test results in table 4, the relationship between the volume content and the maximum crack width was given by figure 16 and equation (16).

\[ \omega_f = 0.212V_f + \omega_f' \ (R^2 = 0.9594) \]  
(16)

where \( \omega_f' \) is maximum crack width of the plain concrete.
5.4. Fracture Energy

The fracture energy of concrete is an important parameter to characterize the energy consumption in the process of concrete fracture and crack propagation. The greater the fracture energy was, the more the energy consumption in the process of fracture was. The fracture energy of BFRC was more than that of plain concrete. The main reason was that the BFRP needed to consume energy when it was broken. This also indicated that the fracture resistance of BFRP was effective.

Fracture energy specifically referred to the energy consumption of cracks per unit area, which was shown on the curve as the ratio of the area under the load-crack width curve to the cross-sectional area of the specimen, that was, the area under the stress-crack width curve:

\[ G_f = \int_0^\omega \sigma(\omega) \, d\omega \]  \hspace{1cm} (17)

The test results of fracture energy were shown in table 4 and figure 17.

![Fitted curve](image)

**Figure 16.** Relationship between the volume content and maximum crack width.

**Figure 17.** Relationship between the volume content and fracture energy.

It can be seen from figure 17 that the fracture energy of concrete increased with the increase of volume content. The fitted equation between specific fibre volume content and fracture energy was as follows:

\[ G_f = 201.85V_f + G_f' \quad (R^2 = 0.9549) \]  \hspace{1cm} (18)

where \( G_f' \) is maximum fracture energy of the plain concrete.
5.5. Characteristic Length
There are many methods for characterizing the fracture properties of concrete [29, 30]. This paper used the characteristic length proposed by Hillerborg to analyze the fracture properties of BFRC equation (19).

\[ L_{ch} = \frac{E_f G_f}{f_c^2} \]  

(19)

The specific dates of the characteristic length of each specimen were shown in table 4. The characteristic length of concrete was negatively correlated with the brittleness of concrete. According to the test results, it can be found that when the volume content of BFRP increased from 0.1% to 0.4%, the characteristic length of fibre concrete increased from 15.11% to 22.63%. In other words, with the increase of BFRP volume content (no more than 0.4%), the characteristic length of concrete also increased. The above analysis shows that the reasonable incorporation of BFRP can reduce the brittleness of concrete and increase its toughness.

6. Conclusions
Compared with the compression and tensile test of BFRC and plain concrete, the following conclusions were obtained:

1) The optimum volume fraction of basalt fibres is 0.3% and 0.4% within the scope of this study. In this case, the compressive strength, tensile strength, toughness index, fracture energy and characteristic length are significantly improved. With the volume fraction of BFRP exceeding the optimum volume fraction, the mechanical properties of BFRP are weakened.

2) By comparing with the tensile strength, there was no significant improvement in compressive strength. In other words, the incorporation of BFRP can improve tensile strength more than compressive strength.

3) The failure mode of concrete can be changed by the incorporation of BFRP from brittle failure to non-brittle failure. In addition, by observing the failure characteristics of fibres at the failure section, it can be judged that there is a good bonding behavior between BFRP and concrete.

4) The compressive toughness, the tensile toughness of BFRC were evaluated by the advanced evaluation method of toughness, fracture energy respectively and Hillerborg characteristic length. It indicated that the incorporation of BFRP was an adoptable way to improve the toughness of concrete performance and crack resistance.

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