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# Deformation Damage and Energy Evolution of Basalt Fiber Reinforced Concrete under the Triaxial Compression

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**Abstract:** To explore the law of energy evolution and the change of damage before and after specimen failure, the conventional triaxial compression tests (5, 10, 15, 20, and 30 MPa) of basalt fiber reinforced concrete (BFRC) with different fiber volume fractions (0, 0.2% and 0.4%) were carried out by MTS816 rock testing system, and the cyclic loading and unloading tests of BFRC with a fiber content of 0.2% were carried out. The experimental results show that the peak strength and strain of BFRC increase with the increase of confining pressure. Tensile failure occurs under low confining pressure, and shear failure occurs under high confining pressure. The best volume fraction of fiber is 0.2%. Under different confining pressures, the input energy, elastic energy, plastic properties, and dissipated energy of the samples first increase and then decrease to a stable level. The elastic energy and dissipated energy reach the maximum near the peak stress, while the input energy and plastic properties reach the maximum at the peak. At the same time, the damage increases continuously with the input of load under different confining pressures, indicating that the failure of the specimen is a process of energy accumulation.

**Key words:** basalt fiber reinforced concrete; triaxial compression; cyclic loading and unloading; energy evolution

**CLC number:** TU528.79

## 0 Introduction

Concrete materials are the most widely used materials in the construction field. From January to November 2020, the cumulative output of concrete enterprises above the designated size across the country is  $2.520\ 702\ 4 \times 10^9\ \text{m}^3$ , with a year-on-year increase of

2.49%. Due to the shortcomings of ordinary concrete, such as poor toughness and easy cracking, its limitations are undeniable in actual engineering. It is one of the feasible methods to add fiber polymer to concrete to improve its mechanical properties. Reinforcing materials have developed from asbestos to various fibers. Incorporating polymers enhances the bond strength between the

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fiber and the concrete, which fully utilizes the fiber reinforcement effect and improves the mechanical properties of concrete<sup>[1]</sup>. Basalt fiber has the advantages of good mechanical properties, low price, and no pollution, so it has gradually become the object of popular research<sup>[2-4]</sup>. Dong *et al*<sup>[5]</sup> mixed basalt fibers with 5 different contents into concrete, and the results showed that the basalt fiber reinforced concrete (BFRC) exhibited a brittle failure. Compared with plain concrete, the 28-day compressive strength of BFRC increased by 5%-10%, the flexural strength increased by 21% to 29%, and the impact resistance increased by 0.4 to 2.1 times. Lin *et al*<sup>[6]</sup> conducted uniaxial and triaxial compression tests on BFRC with different fiber lengths (6, 12, 18 mm) and content (0.2%, 0.4%, 0.6%). The results showed that the optimal blending volume fraction is 0.2%, and the uniaxial compressive strength of the BFRC of the three fiber lengths is increased by 10.06%, 11.21%, and 23.57%, respectively; The peak stress of BFRC increases with the increase of confining pressure, and the growth is positively correlated with fiber content and length. Wang *et al*<sup>[7]</sup> studied the influence of basalt fiber volume fraction (0-0.4%) and fiber length (13-36 mm) on the mechanical properties of concrete with different strengths. The results showed that adding a small amount of short basalt fiber can significantly improve the compressive strength and modulus of rupture of BFRC; As the length of basalt fiber increases, the development of early shrinkage cracks first decreases and then slowly increases. The optimal fiber length is 18 mm.

Liang *et al*<sup>[8]</sup> used an independent 10 MN micro-computer-controlled electro-hydraulic servo large-scale multifunctional dynamic and static triaxial instrument and the triaxial apparatus to conduct cyclic loading and unloading experiments on concrete at different loading rates. The theoretical model is established using the mathematical equation through the same points of the experimental curve and the typical trajectory. The relative ratio of the cyclic loading and unloading curve to the theoretical curve showed that the damage law of concrete under a low cycle can be calculated to a certain extent. Xu *et al*<sup>[9]</sup> used the AG-250KN-I testing machine to study the evolution of the hysteresis loop formed under cyclic loading and unloading of rock materials. It was obtained that the greater the displacement rate at different rates, the vertical rock displacement and load curve, the more significant the change in slope of the conclu-

sion. Zhao *et al*<sup>[10]</sup> used the MTS815 electro-hydraulic servo rock system for granite to conduct conventional three-axis and cyclic loading and unloading experiments under four different confining pressures. The failure characteristics under the two loading modes are typical brittle failures. The peak stress and crack initiation stress increase linearly with the increasing confining pressure. Compared with conventional triaxial and cyclic loading and unloading experiments, it is found that the peak stress, cracks initiation stress, and Poisson's ratio of cyclic loading and unloading under the same confining pressure are greater than those of conventional triaxial experiments. Xiao *et al*<sup>[11]</sup> conducted cyclic loading and unloading experiments on concrete under different lateral forces and found that the lateral pressure and strain rate affect the hysteresis loop formed by the cyclic loading and unloading curve. Through the analysis of the Weibull statistical distribution model, it was concluded that the rise of lateral stress was related to the increase of dissipation energy.

These researchers have studied BFRC from different angles, showing that the basalt fiber has a specific strengthening and toughening effect on concrete. When the specimen is subjected to an external load, its internal micro defects evolve continuously, gradually form macro cracks, and cause overall instability and failure. The essence of ring breaking is the mutual conversion of energy. Meng *et al*<sup>[12,13]</sup> conducted triaxial cyclic loading and unloading tests on rock samples under six confining pressures using an MTS815 testing machine exploring the influence of confining pressure on the energy evolution characteristics of rock samples. The results showed that the the energy characteristic density of the rock sample was positively correlated with confining pressure. Confining pressure can inhibit the dissipation and release of energy during specimen failure, resulting in the incomplete release of elastic energy. Yang *et al*<sup>[14]</sup> carried out cyclic loads and unloading tests on sandstone under different confining pressures and energy consumption ratio  $\eta$  is introduced, and the characteristics of energy evolution under cyclic loads were investigated. The results showed that  $\eta$  offered a "spoon" evolution as the number of cycles increased, and was negatively correlated with the confining pressure. The theoretical formula of stress-strain development was established.

In this paper, the effects of fiber content and confining pressure on the mechanical properties of C50 con-

crete are studied by conventional triaxial compression tests under five confining pressures on BFRC with different fiber content. Local cyclic loading and unloading tests are carried out for BFRC with a fiber content of 0.2% to explore the process of energy evolution and damaged changes before and after sample failure.

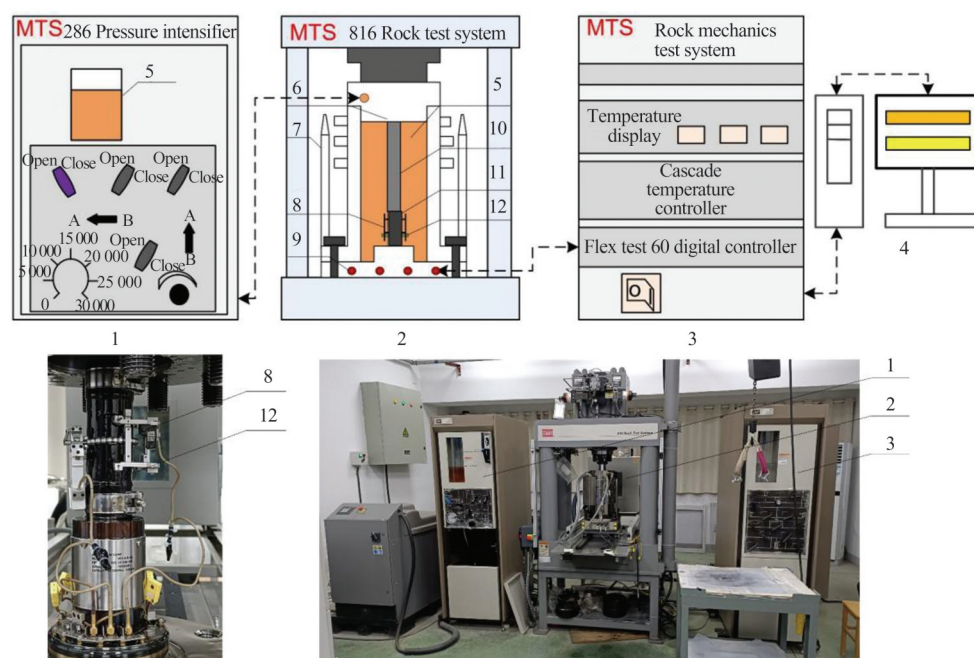
## 1 Test Instrument and Scheme Design

Basalt fiber reinforced concrete with fiber volume fractions of 0.2% and 0.4% are prepared according to the "Standard for Testing the Performance of Ordinary Concrete Mixtures"(GB50080-2002). The specimens were processed into cylindrical shapes of  $\phi 50$  mm(diameter)  $\times H100$  mm (height). The diameter deviation of upper and lower end faces is less than 0.3 mm, and the axial variation is less than  $0.25^\circ$ .

In this test, the MTS816 rock testing system is used to carry out triaxial compression tests of concrete under five confining pressures (5, 10, 15, 20, and 30 MPa). The maximum axial load applied by the testing machine is 2 000 , and the maximum circumferential confining pressure is 137 MPa. The working principle is shown in Fig. 1.

The load is applied to the test piece through the indenter 10. The confining pressure is applied by hydraulic oil 5 injected into the triaxial cavity 6. The deformation of the sample is measured by the axial extensometer 8 and the hoop extensometer 12. The loading mode of load-displacement control is determined after the trial test. The confining pressure is added to the predetermined value according to the hydrostatic pressure and remains constant. The confining pressure loading rate is 5 MPa/min. After the confining pressure is stable at the set value, the axial load is loaded at the rate of 0.005 mm/s until the residual stage of the specimen appears.

To prevent the change of mechanical properties caused by the contact between the sample and the hydraulic oil during the test, we need to add pads at both ends of the sample, wrap it with the latex film, and then seal it with a shrinkable heat pipe. The local cyclic loading and unloading test adopts the axial displacement control cycle process to carry out the loading and unloading in the post-peak stage at a rate of 0.005 mm/s. During the experiment, the constant confining pressure is maintained, and the axial stress is relieved. It can be terminated when there are 2-3 cycles in the residual stage.



**Fig. 1 Schematic diagram of MTS816 Rock Test System**

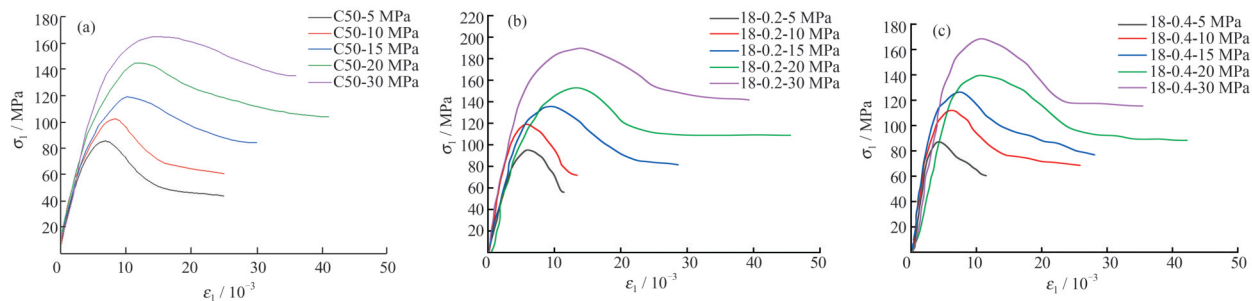
1-Hydraulic circulation control system; 2-Triaxial operating room; 3-Control cabinet; 4-Data collection system; 5-Hydraulic oil; 6-Triaxial cavity; 7-Locating rod; 8-The axial extensometer; 9-The sensor interface; 10-The pressure device; 11-Sample; 12-The circumferential extensometer

## 2 Results and Analysis

### 2.1 Conventional Triaxial BFRC Stress-Strain Curve

The stress-strain curves of BFRC samples with different fiber contents are shown in Fig. 2. From Fig. 2, the stress-strain curve trend of BFRC is similar, and the curve can be divided into four stages: 1) Void pressure compaction stage: Sample internal holes are compacted under the action of external load in a short time. Before deviatoric stress loading, the static water pressure has already combined the internal voids, so in the compaction stage, the stress-strain curve is not obvious through hydrostatic pressure loading. 2) Linear elastic stage: In this stage, the stress-strain relationship is approximately lin-

ear. The deformation can be recovered if the external load is unloaded, and the microcrack in the sample will develop stably with energy dissipation. 3) Unstable failure stage: In this stage, the stress increases slowly, but the strain increases rapidly. Many microcracks are generated in the matrix, resulting in the sample going from a stable structure to a broken structure, and the stress-strain curve changes nonlinearly. 4) Post peak failure stage: Due to the connected propagation of microcrack in the sample, the macro fracture surface is gradually formed, the strain increases rapidly, the stress fluctuates in a small range after falling to the residual strength, and the sample still has an indeed certain bearing capacity. The mechanical property parameters of BFRC obtained according to Fig.2 are shown in Table 1.



**Fig. 2** Conventional triaxial stress( $\sigma_1$ )-strain( $\epsilon_1$ ) curve of C50(a) and BFRC 18-0.2(b) and 18-0.4(c) under different confining pressure

C50: Unadded volume fraction of mixed soil; 18-0.2 and 18-0.4 represent a volume fraction of 18 mm with a volume fraction 0.2% and 0.4%, respectively

**Table 1** Mechanical performance parameters of basalt fiber reinforced concrete

| Confining pressure /MPa | Fiber volume fraction /% | Peak stress / MPa | Stress change rate /% | Peak strain /(mm/mm) | Strain change rate /% | Young's modulus /GPa |
|-------------------------|--------------------------|-------------------|-----------------------|----------------------|-----------------------|----------------------|
| 5                       | 0                        | 84.02             | 0                     | 0.003 4              | 0                     | 39.78                |
| 5                       | 0.2                      | 99.03             | 17.86                 | 0.004 14             | 21.76                 | 38.42                |
| 5                       | 0.4                      | 90.95             | 8.25                  | 0.004 5              | 32.35                 | 31.76                |
| 10                      | 0                        | 103.57            | 0                     | 0.005 51             | 0                     | 40.74                |
| 10                      | 0.2                      | 120.11            | 15.97                 | 0.006 62             | 20.15                 | 39.51                |
| 10                      | 0.4                      | 112.09            | 8.23                  | 0.007 27             | 31.94                 | 29.37                |
| 15                      | 0                        | 116.95            | 0                     | 0.007 36             | 0                     | 36.53                |
| 15                      | 0.2                      | 135.57            | 15.91                 | 0.008 79             | 19.43                 | 32.99                |
| 15                      | 0.4                      | 128.45            | 9.83                  | 0.009 64             | 30.98                 | 32.49                |
| 20                      | 0                        | 141.19            | 0                     | 0.008 91             | 0                     | 34.41                |
| 20                      | 0.2                      | 146.99            | 4.11                  | 0.010 69             | 19.98                 | 34.72                |
| 20                      | 0.4                      | 145.24            | 2.87                  | 0.011 76             | 31.99                 | 32.22                |
| 30                      | 0                        | 160.06            | 0                     | 0.012 08             | 0                     | 32.55                |
| 30                      | 0.2                      | 168.37            | 5.19                  | 0.014 52             | 20.03                 | 31.84                |
| 30                      | 0.4                      | 164.94            | 3.05                  | 0.015 91             | 31.71                 | 26.57                |

Because the concrete has a certain discrete type, as shown in Fig. 3, the Young's modulus values obtained in this experiment are within a reasonable range around the standard Young's modulus of C50 concrete of 34.5 GPa (shown by dotted line in Fig. 3). Basalt fiber with a volume fraction of 0.2% has little effect on the Young's modulus of concrete, but when the content increases to 0.4%, the Young's modulus tends to decrease.

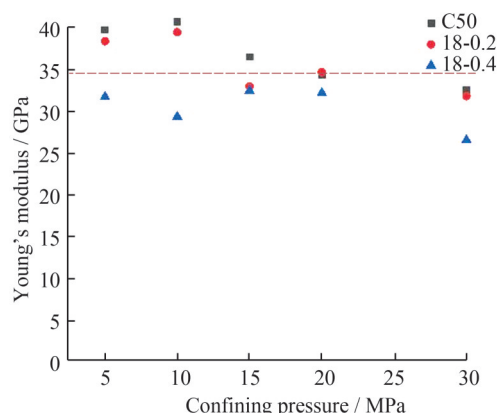


Fig. 3 Young's modulus of BFRC

## 2.2 Effect of Confining Pressure on the Failure of BFRC

Because the confinement of confining pressure limits the propagation speed of microcrack in concrete and effectively slows down its damaged degree, the failure

of concrete after a peak can be studied under the action of confining pressure. Under low confining pressure (5 MPa, 10 MPa), the axial stress of the BFRC specimen decreases rapidly after failure, showing apparent strain softening. After the peak, axial stress decreases slightly under medium and high confining pressures (15 MPa, 20 MPa). Under high confining pressure (30 MPa), the post-peak stress-strain curve tends to be flat without apparent strain softening. With the increase of confining pressure, the post-peak stage of BFRC will gradually change from a strain-softening state to an ideal plastic state. The failure characteristics of the whole specimen are mainly divided into tensile failure and shear failure, and there are some irregular and secondary cracks around the main break. 5 MPa confining pressure has little circumferential restraint on the sample. The tensile strength of the specimen is less than the transverse tensile stress generated by the Poisson effect, so the sample undergoes tensile failure and produces longitudinal cracks (as shown in Fig. 4). Under immense confining pressure, the shear strength of the BFRC sample is less than the shear stress on its inclined section, and shear failure will eventually occur. Figure 5 shows the relationship between BFRC peak stress/strain and confining pressure. It can be seen from Fig. 5 that the higher the confining pressure, the stronger the bearing capacity, and the greater the peak strain at failure.

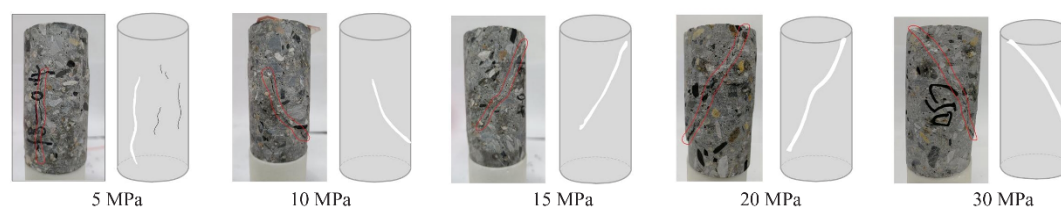


Fig. 4 Failure characteristics of BFRC specimens under triaxial compression

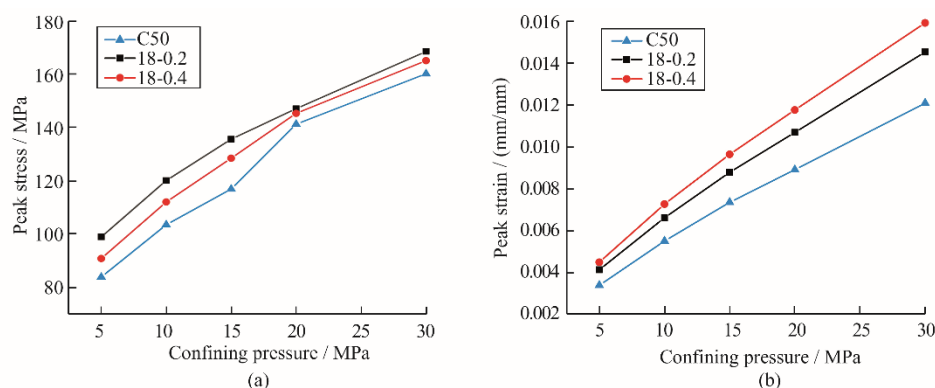


Fig. 5 Relationship between BFRC peak stress (a)/strain (b) and confining pressure

### 2.3 Mechanism of Basalt Fiber Reinforced Concrete

Basalt fiber is an inorganic material, which has high interfacial bond strength with concrete. However, due to the differences in mechanical properties of basalt fiber from different producing areas, the optimal fiber content is different. As shown in Fig. 5, the strength of concrete can be improved by adding basalt fiber with a volume fraction of 0.2% and 0.4%. At a lower confining pressure level (5, 10, and 15 MPa), the peak stress of BFRC with a fiber content of 0.2% is 17.86%, 15.97%, and 15.91% higher than that of C50, respectively; when the fiber content is 0.4%, the peak stress of C50 is increased by 8.25%, 8.23%, and 9.83%, respectively. Under high confining pressure (20, 25, and 30 MPa), compared with C50, the peak stress of BFRC with a volume fraction of 0.2% and 0.4% increased by 4.11%, 5.19% and 2.87%, 3.05%, respectively. The peak strain of BFRC with a volume fraction of 0.2% and 0.4% increased by about 20% and 31%, respectively. Basalt fiber and concrete are silicate materials. Adding basalt fiber to concrete can produce hydration reaction of calcium hydroxide, which belongs to exothermic reaction and can accelerate the hydration reaction of concrete. The mixed crystals and fibers caused by the hydration reaction can form a network structure in the concrete, fill the cracks and voids formed during preparation, hinder the development of cracks and holes and improve the mechanical properties of the sample when it is subjected to load. Under certain circumstances, the length and volume fraction of basalt fiber can improve the strength of concrete. However, due to the heterogeneity of concrete, anisotropy, and discreteness, excessive fibers will reduce the average spacing in the matrix, the adhesion with the matrix is reduced, and the reinforcement effect is re-

duced.

### 3 Energy Evolution Analysis of BFRC under Triaxial Cyclic Loading and Unloading

According to the conventional triaxial test results, the reinforcement effect is enhanced when the fiber content is 0.2%, so only under this working condition, the triaxial local cyclic loading and unloading tests are carried out under different confining pressures. The typical stress-strain curve is shown in Fig. 6. According to Fig. 6, 1) the envelope of BFRC stress-strain curve under cyclic loading is similar to that under continuous loading, and there are compaction, elastic, unstable damage, and post peaking failure stages, indicating that the loading and unloading process does not change the mechanical properties of the sample; 2) In the residual stage, the area of the hysteresis loop changes little, and the residual strength of the sample increases gradually with the increase of confining pressure; 3) The cyclic loading stress-strain curve has a noticeable hysteretic effect. As shown in Fig. 7, the  $i$ -th unloading curve and  $i+1$  loading curve form a closed hysteretic loop, and its area can be characterized by the energy consumed by the compaction of micro-cracks in the sample.

Axial stress in triaxial test  $\sigma_1$  always works positively, and the sample absorbs and stores energy due to axial compression deformation. As the confining pressure  $\sigma_3$  remains unchanged and does not directly lead to sample failure, this paper ignores the circumferential energy and only studies the axial energy evolution behaviors. Assuming that there is no heat exchange with the outside world during axial loading, it can be seen from the principle of energy conservation:

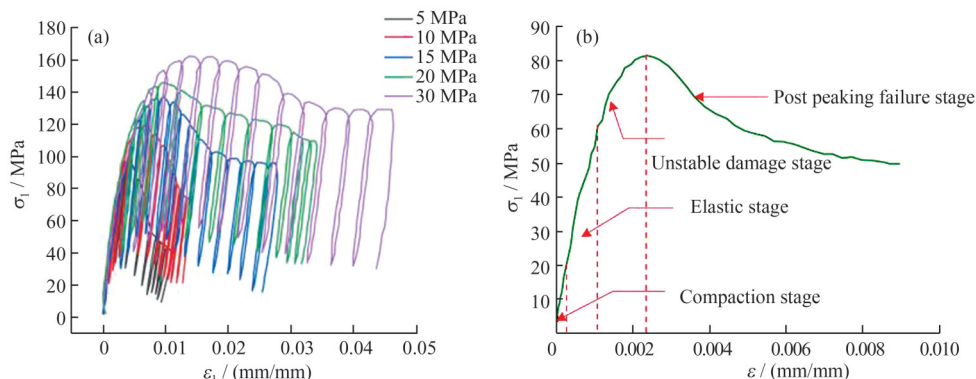


Fig. 6 Stress-strain curve of triaxial cyclic loading and unloading

(a) Cyclic loading and unloading under different confining pressures; (b) Stress-strain evolution curve

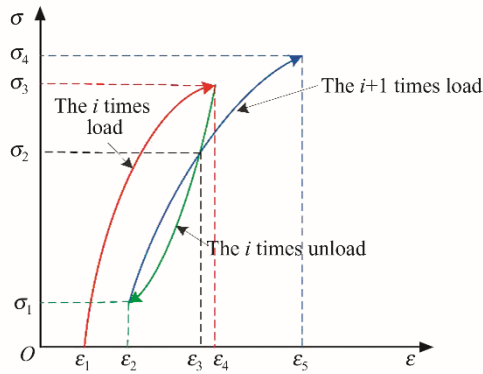


Fig. 7 Schematic diagram of sample energy calculation under cyclic loading and unloading

$$W^0 = W^e + W^p + W^d \quad (7)$$

where  $W^0$  is the total energy input by the testing machine,  $W^e$  is the elastic energy recovered by the sample after load unloading,  $W^p$  is the plastic property of the sample, and  $W^d$  is the energy dissipation by the internal microcrack of the sample being compacted. The input energy, elastic energy, and dissipation energy of the sample during a specific loading and unloading can be calculated by using the stress-strain curve obtained from the triaxial cyclic loading and unloading. As shown in Fig. 7, in the  $i$ -th loading and unloading, the total deformation caused by the loading curve  $\varepsilon_1\sigma_3$  is  $\varepsilon_4 - \varepsilon_1$  and the area enclosed by the abscissa is the total energy input from the outside  $W_i^0$ . The unloading curve  $\sigma_3\sigma_1$  releases the recoverable deformation  $\varepsilon_4 - \varepsilon_2$  and the area surrounded by the abscissa is the elastic energy  $W_i^e$

$$\begin{aligned} W_i^0 &= \int_{\varepsilon_1}^{\varepsilon_4} \widehat{\varepsilon_1\sigma_3} d\varepsilon_i W_i^e \\ &= \int_{\varepsilon_2}^{\varepsilon_4} \widehat{\sigma_3\sigma_1} d\varepsilon_i W_i^d \\ &= \int_{\varepsilon_2}^{\varepsilon_4} (\widehat{\sigma_1\sigma_2} - \widehat{\sigma_2\sigma_1}) d\varepsilon_i W_i^p \\ &= W_i^0 - W_i^e - W_i^d \end{aligned}$$

Various energies  $W^0$ ,  $W^e$ ,  $W^d$  and  $W^p$  of the sample during each cycle under different confining pressures are calculated by the the following formulas.

$$\begin{aligned} W_i^0 &= \int_{\varepsilon_1}^{\varepsilon_4} \widehat{\varepsilon_1\sigma_3} d\varepsilon_i \\ W_i^e &= \int_{\varepsilon_2}^{\varepsilon_4} \widehat{\sigma_3\sigma_1} d\varepsilon_i \\ W_i^d &= \int_{\varepsilon_2}^{\varepsilon_4} (\widehat{\sigma_1\sigma_2} - \widehat{\sigma_2\sigma_1}) d\varepsilon_i \\ W_i^p &= W_i^0 - W_i^e - W_i^d \end{aligned}$$

The evolutionary curve with strain (cycle times) is shown in Fig. 8. According to Fig. 8, various energies of

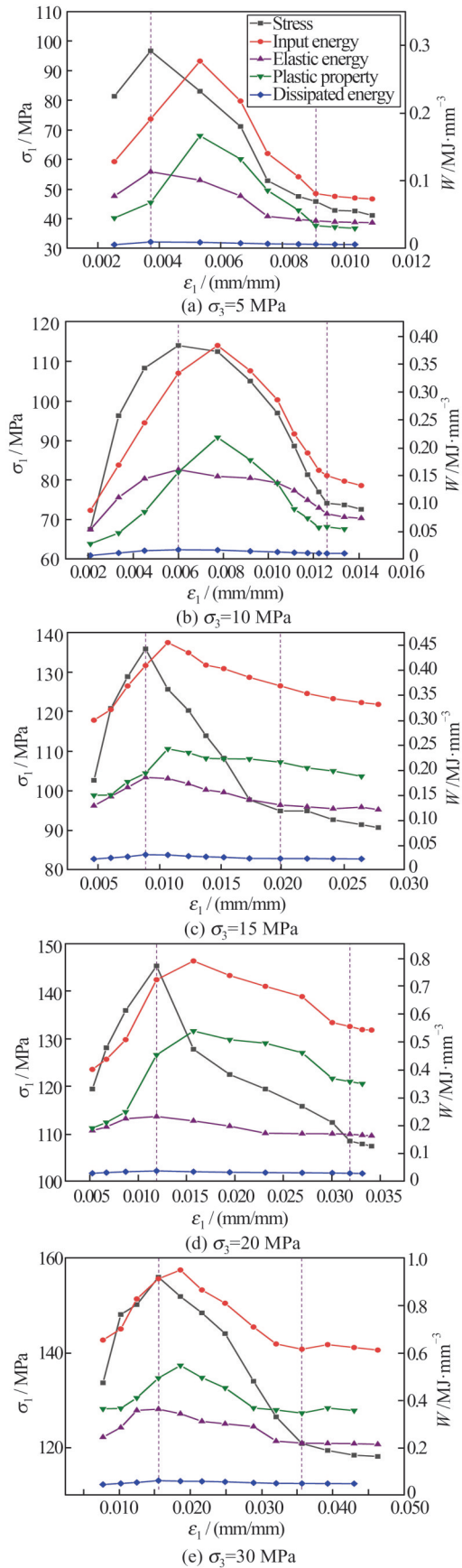


Fig. 8 BFRc stress-strain-energy curve under cyclic loading and unloading

BFRC samples under different confining pressures increase first and then decrease to a stable level. The elastic energy  $W^e$  and dissipated energy  $W^d$  reach the maximum near the stress peak, and the input energy  $W^0$  and plastic property  $W^p$  reach the maximum after the peak. The energy  $W^d$  (area of hysteresis loop) consumed by microcracks in the sample is always less than the accumulated  $W^d$ . When  $\sigma_3 = 5$  and 10 MPa, the energy decreases sharply after the inflection point; when  $\sigma_3 = 15, 20$  and 30 MPa, the energy decreases slowly due to the restraint of confining pressure. The stage characteristics of the curve of energy evolution of the loaded sample are: 1) In the pre-peak stage, the testing machine continues to work on the sample, and  $W^0$ ,  $W^e$ ,  $W^p$  and  $W^d$  all follow  $\sigma_1$ .  $W^e$  accumulated by the specimen is greater than  $W^p$  when  $\sigma_3 = 5$  and 10 MPa, but lower than  $W^p$  when  $\sigma_3 = 15, 20$  and 30 MPa, which may be due to the rapid increase of  $\sigma_1$  under  $\sigma_3 = 15, 20$  and 30 MPa and the reduced local unloading capacity; 2) In the post-peak failure stage,  $W^e$ ,  $W^d$ ,  $W^0$  and  $W^p$  decrease after reaching the maximum. In this stage, the micro-cracks in the sample expand into the macro fracture surface, re-

sulting in the release of stored elastic energy and increased plastic properties; 3) In the residual stage, although the sample has been damaged, it still has an indeed certain bearing capacity due to the action of confining pressure, and the energy is maintained at a relatively stable level.

According to Fig. 9, the trends in the energy evolution of BFRC under different confining pressures are very similar. The energy of the sample increases first and then decreases with the number of cycles, showing a nonlinear change. The maximum value of  $W^0$ ,  $W^e$ ,  $W^p$ , and  $W^d$  increase with the increase of confining pressure, indicating that the higher the confining pressure is, the more the elastic energy accumulated in the sample is, and the more work  $\sigma_1$  needs to do to destroy the sample. The numerical values of residual  $W^e$  under 5, 10, 15, 20, 30 MPa are 0.038 24, 0.073 30, 0.120 62, 0.163 15, and 0.214 21 MJ/mm<sup>3</sup>, respectively. Compared with  $\sigma_3 = 5$  MPa, the values of  $W^e$  under 10, 15, 20, 30 MPa are increased by 92%, 115%, 227% and 360%, respectively, indicating that the higher the confining pressure, the less the completeness of the elastic energy released during

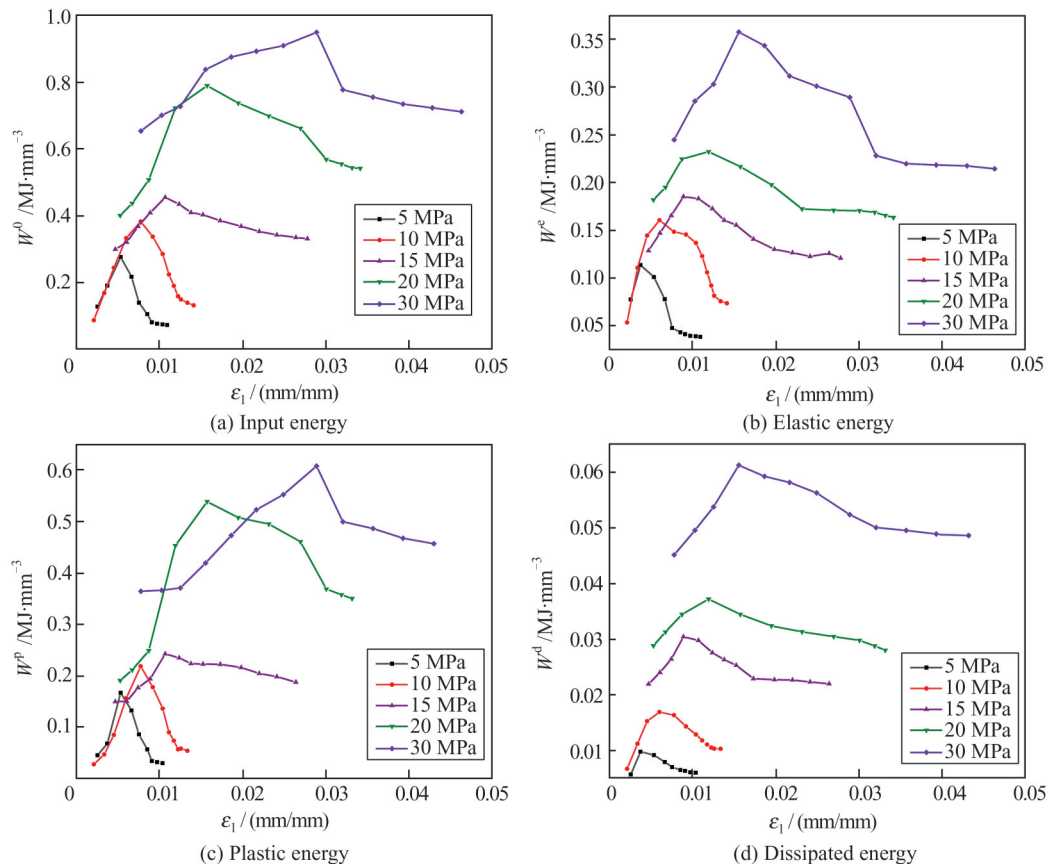


Fig. 9 Energy evolution curve of BFRC under different confining pressures

the instability and failure of the sample (Fig. 9(b)). From the energy point of view, the deformation and failure of the sample can be understood as the process of energy dissipation and release. The damage caused by instability results from the rapid release of the elastic energy accumulated inside.

During the loading process of concrete samples, part of the energy is absorbed and transformed into elastic energy, which are released with the unloading of the load, and used for the internal damage and plastic defor-

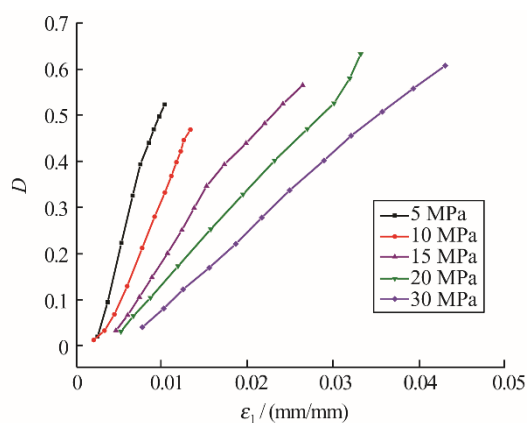
mation of the sample, resulting in the irreversible change of the internal structure. The damage factor  $D$  is defined as the ratio of the sum of incremental plastic energy and dissipated energy of the specimen to the cumulative input energy at the last loading<sup>[15, 16]</sup>. The damage factors of BFRC under different confining pressures can be ob-

tained according to  $D(i) = \frac{\sum_1^i (W_i^p + W_i^d)}{\sum_1^k W_k^0}$ , and the results are shown in Table 2.

**Table 2** Damage factor of BFRC under cyclic loading and unloading

| Cycle | Confining pressure /MPa |          |          |          |          |
|-------|-------------------------|----------|----------|----------|----------|
|       | 5                       | 10       | 15       | 20       | 30       |
| 1     | 0.019 45                | 0.012 11 | 0.032 83 | 0.030 63 | 0.039 93 |
| 2     | 0.094 16                | 0.032 59 | 0.066 17 | 0.064 45 | 0.080 49 |
| 3     | 0.222 75                | 0.067 85 | 0.105 08 | 0.103 96 | 0.121 89 |
| 4     | 0.325 28                | 0.128 84 | 0.148 03 | 0.172 37 | 0.168 77 |
| 5     | 0.393 16                | 0.211 58 | 0.200 19 | 0.252 35 | 0.220 68 |
| 6     | 0.439 3                 | 0.279 3  | 0.250 45 | 0.327 71 | 0.277 38 |
| 7     | 0.468 71                | 0.331 83 | 0.298 3  | 0.401 18 | 0.336 75 |
| 8     | 0.496 35                | 0.367 68 | 0.345 8  | 0.469 72 | 0.401 17 |
| 9     | 0.522 61                | 0.397 48 | 0.392 74 | 0.525 32 | 0.454 78 |
| 10    | —                       | 0.421 2  | 0.438 46 | 0.579 21 | 0.507 07 |
| 11    | —                       | 0.445 31 | 0.481 93 | 0.631 97 | 0.557 45 |
| 12    | —                       | 0.467 97 | 0.524 16 | —        | 0.606 75 |
| 13    | —                       | —        | 0.564 29 | —        | —        |

From the damage factor strain curves under different confining pressures (Fig. 10), we can further explore the influence of confining pressure on damage factors.



**Fig. 10** The damage factor-strain curves of BFRC under different confining pressures

The curve is approximately linear, and the intact damage factor of the sample before loading is 0. The damage factor increases with the increase of strain. Moreover, the lower the confining pressure, the steeper the curve, indicating that the damage factor increases slowly due to the inhibition of specimen damage by high confining pressure. The damage factors under different confining pressures are less than 1, indicating that the specimen has not entirely lost its bearing capacity, which is confirmed in the residual stage of the stress-strain curve.

## 4 Conclusion

In this paper, the effects of fiber content and confining pressure on the mechanical properties of concrete are studied through the conventional triaxial compression tests of BFRC with different fiber content under dif-

ferent confining pressure. The local cyclic loading and unloading tests are carried out for BFRC with a fiber content of 0.2%. The peak strength and strain of BFRC increase approximately linearly with the increase of confining pressure. Tensile failure occurs under low confining pressure, and shear failure occurs under high confining pressure. The peak strength of BFRC with 0.2% and 0.4% fiber content increased by 17.86%, 15.97%, 15.91%, and 8.25%, 8.23%, and 9.83%, under low confining pressure of 5, 10, 15 MPa, and increased by 4.11%, 5.19%, 2.87%, and 3.05% under high confining pressure 20 and 30 MPa, respectively. The peak strain of BFRC with 0.2% and 0.4% fiber content increased by about 20% and 31%, respectively.

In the cyclic loading and unloading test, the stress-strain curve of the BFRC sample has the obvious hysteretic effect, which shows that the sample does not completely store the energy input by the testing machine, and part of the energy is dissipated with the generation of cracks. The stress-strain curve can calculate the input energy, elastic energy, plastic property, and dissipation energy in each loading and unloading process. The energy of samples under different confining pressures increases first and then decreases to a stable level. The elastic energy  $W^e$  and dissipated energy  $W^d$  reach their maximum values near the stress peak, while the input energy  $W^0$  and plastic property  $W^p$  reach their maximum after the peak. If the confining pressure is higher, the less complete the elastic energy released during the instability and failure of the sample.

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