Characterization and mesosimulation of the triaxial compression failure of rock-like materials

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Abstract. The laboratory tests and the numerical simulation of the particle flow code of triaxial compression are conducted to analyze the fractal dimensions of fracture surface, strength properties, energy dissipation, damage patterns, and crack evolution. The following results are obtained. (1) Under low confining pressure, the fracture surface of a brittle specimen is rough, and the angle relative to the maximum principal stress is small. The specimen eventually exhibits a local tensile–shear failure mode. As the confining pressure increases, the strength of the specimen increases, and the yield platform for the stress–strain curve is more obvious. The main fracture surface flattens, and the fracture angle increases as the confining pressure increases. The specimen macroscopically exhibits a shear failure mode. (2) As the confining pressure increases, the trend of transgranular shear failure becomes obvious, and the microfracture surface has a smaller fractal dimension. (3) In the triaxial compression test, energy is stored, dissipated, and released. When the storage limit is reached, the internal elastic strain energy becomes released sharply, and the damage variable increases rapidly. (4) As the confining pressure increases, the number of tensile and shear cracks accumulates in an “S” shape, and the proportion of shear cracks increases gradually.

1. Introduction
The strength and deformation characteristics of deep rock mass are the basis of theoretical calculation and engineering design, and they are among the important subjects of rock mechanics and engineering research. Many scholars have carried out related in-depth research.
For example, Yang S Q et al. [1] investigated the marble specimens with medium and coarse grains and systematically analyzed the strength and deformation properties of the marble specimens under conventional triaxial compression. Zhu Q Z et al. [2] used siltstone as a research object and analyzed the relationship between the size effect of specimens and the rock characteristics of strength and deformation under different confining pressures. On the basis of the strength of rocks under different confining pressures, You M Q [3], Singh M [4], and others constructed nonlinear strength criteria, such as exponential and parabola types, which represent the strength of rocks. Crack initiation, propagation, cohesion, and penetration under energy result in the deformation of rock (rock mass) under the action of external force and instability after the bearing strength is reached [5-7]. Therefore, energy conversion and crack spatiotemporal evolution should be explored to reveal the internal mechanism of the destruction of deep rock mass. The discrete element analysis of particle flow code (PFC) has been widely performed in geotechnical engineering. A particle numerical model is constructed from a mesoscopic point of view to reflect the continuous nonlinear stress–strain relationship of a material and the process of crack initiation and propagation evolution through the failure of the contact between particles [8-9]. At the same time, the discrete element analysis of PFC can track the real-time state of energy storage, release during the loading process, and restore the origin of mechanical behavior to the maximum extent. For example, Cao R, Zhang G K et al. [10,11] conducted a particle flow numerical simulation experiment to analyze the mechanical properties of rocks under uniaxial dynamic compression from the perspective of micromechanics and reveal the laws of energy dissipation, crack propagation, and damage evolution. Zhang X P, Li X F [12,13] studied the mechanical properties of rocks through a direct shear test. They examined the shear strength characteristics and failure patterns of rocks from a macro perspective and discussed the patterns of crack development and energy conversion from a micro perspective. In comparison with laboratory tests, the discrete element method of PFC can be used to simulate the properties of rock mass, thereby solving the challenge of simulating behaviors at a mesoscale.

In this study, the mechanical properties and fracture characteristics of brittle model specimens are studied through a laboratory triaxial compression test. Then, in combination with the particle flow discrete element method, the internal mechanism of rock failure and instability under different confining pressures is further revealed in terms of stress field, energy evolution, crack characteristics, and damage degree. In the following part of this paper, Section 2 presents the laboratory test, including the test design and the analysis of laboratory test results. Section 3 focuses on the numerical model in discrete element method, which elucidates the contact constitutive model, model creation and verification, and analysis of numerical simulation results. Section 4 summarizes the whole study.

2. Laboratory test

2.1. Test design

An α-type high-strength gypsum is selected for the preparation of a brittle model specimen, and the water cement ratio (the mass ratio of water and gypsum) of the specimen is 1:2.7 in accordance with previously described methods [14,15] on brittle materials. Cylindrical specimens with dimensions of Φ50 mm × 100 mm and Φ50 mm × 30 mm are made in
accordance with the international rock mechanic test standard [16] (Figure 1). The p-wave velocity (about 2780 m/s) is measured using a Pundit Lab ultrasonic detector.

(1) In a triaxial test, a high-temperature and high-pressure dynamic rock triaxial apparatus (RTX-1000; Figure 2) is used to conduct four groups of tests with confining pressures of 0, 5, 15, and 25 MPa. Two parallel tests are performed under each confining pressure.

(2) In a Brazil split test, four groups of parallel tests are carried out by using an electrohydraulic servo universal testing machine with a loading rate of 0.05 mm/min.

2.2. Macromechanical characteristics

In Figure 3, the initial stage of the stress–strain curve shows only a slight initial compaction characteristic at 0 MPa confining pressure because of the compact structure of the specimen. Once the post-peak stage is reached, the axial stress decreases rapidly because of the local stress concentration. Failure suddenly occurs, and it is accompanied with a clear and crisp sound. The brittleness characteristics of the specimen are obvious. When the confining pressures are 5, 15, and 25 MPa, the stress in the rock specimen becomes gradually dispersed to the surrounding, and more cracks form near the peak strength point. The stress–strain curve shows a yield plateau, and the larger the confining pressure is, the more obvious the yield plateau will be. The specimen exhibits certain plastic characteristics. Furthermore, the strength decreases gradually as deformation increases, but it does not reach zero. This result indicates that the damaged specimen retains a certain bearing capacity, that is, a certain residual strength.

When the confining pressure increases from 0.0 MPa to 25 MPa, the peak stress and strain of the specimen increase. When the peak strength increases from 29.2 MPa to 76.8 MPa, the peak strain increases from 0.307% to 0.612%. The test results are consistent with the conclusions of rock mechanics theory and similar tests [1,17]. In Figure 4, the relationship between the peak strength and the confining pressure is reflected by Mohr’s envelope. The cohesive force (c) and the internal friction angle (φ) are 10.1 MPa and 19.52°, respectively.
2.3. Analysis of failure modes

The failure modes of the specimens are shown in Figure 5. At 0 MPa, the main crack develops along the axial direction, and the specimen exhibits a split--shear composite failure mode, forming a large strip debris. At 5–25 MPa, the specimen is dominated by the overall shear failure, generating a single macrofracture surface. Furthermore, the fracture surface starts at the top of the specimen with a fracture angle of 75° at 5.0 MPa. The fracture angles reach 73° and 69° at 15.0 and 25.0 MPa, respectively. These results suggest that the confining pressure restrains the occurrence of the local failure of the specimen. As the confining pressure increases, the specimen changes from a local split–shear failure mode to an overall shear failure mode, and the position of the slip shear zone changes constantly as the fracture angle decreases.

Figure 6 illustrates the typical morphological characteristics of the macrofracture surfaces of the specimens. In the compression test at 0 MPa, the cross-section often shows irregular undulations, and the fracture surface is rough. At 15 MPa, the main fracture surface of the rock is relatively flat and smooth, the roughness decreases significantly, and the powder generated by a certain friction effect is attached to the fracture surface. These results indicate that crack propagation and sliding occur during failure.
Figure 6. Macrosection morphological characteristics of the specimens
(a) Cross-section of the specimen at a confining pressure of 0 MPa
(b) Cross-section of the specimen at a confining pressure of 15 MPa

2.4. Analysis of the mesomorphology of the fracture surface

Rock failure is actually a gradual development process from mesomorphology to macromorphology. On the mesoscale, the fracture, slip, and dislocation of crystals develop and accumulate gradually; as a result, macroscopic deformation and cracking occur, eventually leading to the instability and failure of rocks. The two movement mechanisms have a certain relationship [18]. In the present study, a JSM-7200F thermal field emission scanning electron microscope is used to observe the debris microstructure of multiple groups of specimens at confining pressures of 0–25 MPa (Figure 7).

Figure 7. Microelectron micrograph of the microfracture surface (×1500)
Confining pressures of (a) 0, (b) 5, (c) 15, and (d) 25 MPa

When the confining pressure is low, most of the crystals inside the specimen are acicular and rod shaped, showing intergranular failure. The local crystals have a spherical or pie-shaped structure, and the transgranular fracture forms between a small number of particles. In general, the crystals on the surface of the structure are relatively complete, and the intergranular tensile failure and partial transgranular shear failure occur on microfracture surfaces. As the confining pressure increases, the crystal particles compress and slide against one another, and
a large number of crystal fracture marks appear on the structural surface. The crystal on the surface is spherical or pie shaped, that is, the microfracture surface mainly experiences transgranular shear failure.

The roughness of the microfracture surface can characterize the undulation of a microfracture surface crystal, which reflects the failure mode of the fracture surface to some extent [19]. In the present study, the microscopic three-dimensional structures corresponding to different microfracture surfaces are created with MATLAB (Figure 8). The fractal dimensions of the microfracture surfaces are calculated with the fractal geometry method [20] to characterize the undulation state of the microfracture surfaces.

Figure 8. Three-dimensional surface morphology of a microfracture surface
Confining pressures of (a) 0, (b) 5, (c) 15, and (d) 25 MPa

A small cube with a side length \( r \) is taken, and the number of small cubes \( (N_r) \) that completely cover the three-dimensional surface morphology is calculated. If the minimum and maximum height values of the measured fractal body fall in the \( K \)th and \( L \)th cubes, respectively, then

\[
n_r(i, j) = L - K + 1,
\]

where \( n_r(i, j) \) is the number of small cubes required to cover the fractal bodies in the grid \((i, j)\). The number of cubes \( N_r(i, j) \) required to cover the entire fractal body is expressed as

\[
N_r(i, j) = \sum_{i,j} n_r(i, j).
\]

\( N_r \) can be obtained at different measurement scales by changing the box scale \( r \) and repeating the above process. The fractal dimension \( (D_r) \) of the microfracture surface is determined via the unary linear regression of the variate \( \ln(1/r) \) and \( \ln N_r \).

\[
D_r = \lim_{r \to 0} \frac{\ln(N_r)}{\ln(1/r)}.
\]
Figure 9. Calculation of fractal dimension
Confining pressures of (a) 0, (b) 5, (c) 15, and (d) 25 MPa

In Figure 9, at 0, 5, 15, and 25 MPa, the microfracture surfaces have \( D_s \) of 2.381, 2.269, 2.157, and 2.109, respectively. \( D_s \) decreases, that is, the main microfracture surface transforms from a rough and loose crystal tensile–shear failure mode to a relatively flat crystal shear fracture mode.

3. Particle flow numerical test
Particle flow numerical simulation is a discrete element method that can be used to construct any rock shape into a particle aggregate. The macroscopic mechanical properties of rocks are simulated through an interaction between particles, and the crack generation of a rock material is simulated with the fracture of bonds between particles to replace the complex fracture mechanics formula involved in other methods. Therefore, this method provides obvious advantages in simulating rock fracture and crack development [21-22].

3.1. Contact constitutive model
A flat-joint contact model [23] is used in this study. The contact and its corresponding flat-joint material are illustrated in Figure 10. The contact simulates the behavior of an interface between two notional surfaces, and each surface is connected to a piece of a body. The flat-joint material is composed of bodies joined by flat-joint contacts such that the effective surface of each body is defined by the notional surfaces of its pieces. These pieces in turn interact at each flat-joint contact with the notional surface of the contacting piece.
Figure 10. Flat-joint contact (left) and flat-joint material (right)

The flat-joint model provides the macroscopic behavior of a finite-size, linearly elastic, and either bonded or frictional interface that may sustain partial damage (Figure 11). The behavior of a bonded element is linearly elastic until the strength limit is exceeded and the bond breaks, thereby causing the element to become unbonded. The bond breakage can describe the mesocharacteristics of rock failure.

The behavior of an unbonded element is linearly elastic and frictional, and slip is accommodated by imposing a Coulomb limit on the shear force, as expressed in Equation (4):

$$
\tau_b = \begin{cases} 
-\mu_b \hat{\sigma}, & \hat{\sigma} < 0 \\
0, & \hat{\sigma} \geq 0
\end{cases},
$$

where $\mu_b$ is the friction coefficient.

For the bonded part, shear strength ($\tau_b$) is

$$
\tau_b = c_b - \hat{\sigma} \tan \phi_b,
$$

where $c_b$ is the cohesion force, and $\phi_b$ is the internal friction angle. If the shear load ($\hat{\tau}$) is greater than $\tau_b$, shear failure occurs. If the normal tensile load ($\sigma_n$) is greater than the normal strength ($\sigma_n$), tensile failure occurs.
Figure 11. Behavior and rheological components of the flat-joint model.

3.2. Model creation and verification

In the Brazil split test model, a circular cylinder specimen with a size of φ 50 mm × 30 mm is established, and the upper and the lower walls are generated (Figure 12). The model contains 12,877 particles. Spherical particles are added at the contact between the loading walls and the specimen to reach the actual loading conditions, and the load is applied through the movement of the upper and lower rigid walls. The movement rate of the walls is $3.2 \times 10^{-9}$ m/step, which satisfies the requirement of quasi-static loading [1].

In the triaxial compression test model, a circular cylinder specimen with a size of φ 50 mm × 100 mm is established. The upper wall, the lower wall, and the side walls are generated (Figure 13). The model contains 26,809 spherical particles. The side walls are controlled with the Fish servo function to maintain a stable confining pressure. The axial loading is applied through the movement of the upper and lower walls, and the movement rate of the walls is $3.2 \times 10^{-9}$ m/step.

Table 1. Microparameters of the PFC model

| $\rho$  | $N$  | $\lambda$ | $E$  | $k_n/k_s$ | $\sigma_b$ | $c_b$ | $\mu_b$ |
|--------|------|-----------|------|-----------|------------|-------|---------|
| kg/m$^3$ | /    | /         | GPa  | /         | MPa        | MPa   | /       |
| 2680   | 4.0  | 1.0       | 11.6 | 2.8       | 1.9        | 18.0  | 0.6     |

$\rho$, density; $N$, number of elements in radial direction; $\lambda$, radius multiplier; $k_n/k_s$, stiffness ratio; $\sigma_b$, tensile strength; $c_b$, cohesion; and $\mu_b$, friction coefficient.

Figure 12 shows the comparison curve between the laboratory triaxial compression test and the numerical simulation test at 5 MPa. The peak strengths are 36.6 and 36.2 MPa, the elasticity moduli are 14.3 and 13.6 GPa, and Poisson’s ratios of the specimen are 0.30 and 0.29, respectively. The macroscopic mechanical parameters agree well. The local tensile–shear failure is formed at the end of the model specimen, and the shear failure zone is generated diagonally. This finding is basically consistent with the failure observed in the laboratory test. Figure 15 presents the results of the Brazil split test. The specimen encounters...
radial tensile failure along the loading direction and is split by the fracture surface into two pieces. No small debris is detected. The peak strengths are 3.80 and 3.85 MPa. The laboratory test and numerical simulation curves are consistent. Therefore, the numerical PFC model generated with the microparameters in Table 1 can be used to simulate the mechanical properties of a brittle gypsum specimen and can accurately reflect its failure characteristics.

**Figure 14.** Comparison diagram of the triaxial compression test (5 MPa)

**Figure 15.** Comparison diagram of the Brazil split test

3.3. Characteristics of energy conversion

3.3.1. Energy mechanism of particle flow

The discrete element method of PFC allows tracking the storage and release of energy in simulation and greatly helps enhance the understanding and analysis of test results [28]. The flat-joint model [19] provides two energy partitions: strain energy \((E_k)\) stored in spring and slip energy \((E_w)\) defined as the total energy dissipated by frictional slip. In numerical simulation, the specimen is loaded through rigid walls, and the input energy is equal to the total work done by the walls. Boundary work \((E_w)\) is the work done by the boundary wall and calculated as follows:

\[
E_w = E_w - \sum_{i=1}^{N_w} (F_i \Delta U_i + M_3 \Delta \theta_3),
\]

where \(N_w\) is the number of walls; \(F_i\) and \(M_3\) are the resultant force and moment of the walls in the current time step, respectively; and \(\Delta U_i\) and \(\Delta \theta_3\) are the displacement and rotation, respectively.

Kinetic energy \((E_k)\) is the energy consumed by the translation and rotation of all the particles, and it is expressed as follows:

\[
E_k = \frac{1}{2} \sum_{i=1}^{N_p} \sum_{j=1}^{N_p} \xi_{ij} \nu_{ij}^2,
\]

where \(\xi_{ij}\) is the generalized mass, and \(\nu_{ij}\) is the generalized velocity.

Strain energy \((E_s)\) is obtained by summing the strain energy in each element:

\[
E_s = \sum_{V_s} E_s^{(e)}.
\]

The strain energy in each element is updated in accordance with the force–displacement law:
\[ E_s^{(e)} = \frac{1}{2} \left( \frac{F_n^{(e)}}{k_n A_n^{(e)}} \right)^2 + \frac{M_n^{(e)}}{k_n I_n^{(e)}} + \frac{(M_n^{(e)})^2}{k_n J_n^{(e)}} \],

with

\[ I^{(e)} = \int \eta^2 \, dA = \begin{cases} \frac{(2/3)T^3}{2} & (t = 1) \\ (1/4)\pi t^4 \cdot 3D \end{cases}, \]

\[ J^{(e)} = \int (\varepsilon^2 + \eta^2) \, dA = \begin{cases} 0,2D(t = 1) \\ (1/2)\pi t^4 \cdot 3D \end{cases}, \]

\[ \tau_e = \sqrt{A^{(e)}/\pi}, \]

where \( I^{(e)} \) is the moment of inertia of the cross-section of the element (about the line passing through \( x^{(e)} \) and in the direction of \( \theta_b \)), and \( J^{(e)} \) is the polar moment of inertia of the cross-section of the element (about the line through \( x^{(e)} \) and in the direction of \( \overline{n}_b \)), \( T \) is the half-length of the element, and \( r_e \) is the effective radius of the element.

The slip energy in the flat joint is obtained by summing the slip energy in each element:

\[ E_{\mu} = \sum_{e} E_{\mu}^{(e)}. \]  

The slip energy in each element is updated in accordance with the force–displacement law whenever the shear-strength limit is exceeded via

\[ E_{\mu}^{(e)} = E_{\mu}^{(e)} + \tau_e^{(e)} A^{(e)} \Delta \delta_e^{(e)}. \]

### 3.3.2. Triaxial loading test of the characteristics of energy conversion

Energy conversion is an essential feature of various physical changes. Triaxial compression failure is a comprehensive process of energy storage, dissipation, and release. According to the first law of thermodynamics,

\[ U = U_c + U_d, \]

where \( U \) is the total energy obtained by the system, \( U_c \) is the elastic strain energy, and \( U_d \) is the dissipation energy.

In this numerical simulation test, the work done by the walls is the total input energy \( (E_w) \), and the accumulated strain energy of all elements in the model is the elastic strain energy \( (E_s) \). The difference between \( E_w \) and \( E_s \) stored during loading is defined as the dissipation energy \( (E_d) \). The loading test at 0 MPa in Figure 16 (b) is taken as an example for analysis.

At the initial loading stage (Section OA), the specimen is under less stress, and no relative slip exists between particles. The friction energy \( (E_u) \) and \( E_k \) of the particle are basically zero without energy dissipation, and the boundary work (energy) is fully converted into \( E_s \) that can be released by the specimen. With a low initial load, \( E_w \) and \( E_s \) are low, the growth rate is relatively slow, and the stress–strain curve of the specimen increases linearly.

At the linearly elastic stage (Section AB), the load increases, and the curves of \( E_w \) and \( E_s \) show strain hardening characteristics as the test proceeds. With the appearance of a small number of cracks, \( E_d \) and \( E_u \) increase slightly, the curves of \( E_w \) and \( E_s \) are separated, and the stress–strain
curve of the specimen still shows a linear growth trend. At the plastic yield stage (Section BC), when the stress reaches 84.9% of the peak strength, $E_d$ and $E_u$ show a downward convex growth at a small rate, and $E_d$ grows faster, indicating that other types of energy, such as crack surface energy, are generated in $E_d$. The growth rate of $E_w$ decreases because of the initiation of microcracks in the specimen and the deterioration of the structure. At the same time, the released $E_s$ is not enough to offset the strain energy generated via loading. $E_s$ still increases, but the growth rate gradually decreases and reaches zero near point C.

At the post-peak failure stage (Section CD), when $E_s$ reaches the extreme value at the stress peak point C, that is, the storage limit of $E_s$ is reached. The specimen is destroyed, and $E_s$ is released rapidly. The external input energy is mainly converted into $E_d$. It leads to a rapid increase in the proportion of $E_d$ and $E_u$ in the total energy and makes them dominant. The stress–strain curve of the specimen drops and enters the strain softening stage. In the whole process, the ratio of $E_d$ to the system energy is extremely small, which is related to the loading process and the internal dynamic balance of the specimen. This result shows that the deformation of the specimen is not severe, and the cracks propagate steadily. Under the action of energy driving, microcracks are formed in the specimen. $E_u$ dissipates because of the relative sliding of the cracks, and $E_u$ accounts for 14.3% of the total energy dissipation, which should be considered.

Figure 16. Energy conversion under different confining pressures

Confining pressures of (a) 0, (b) 5, (c) 15, and (d) 25 MPa

Figure 17 shows the relation curve between confining pressure and energy. As the confining pressure increases, the total energy absorbed by the specimen at the peak point increases continuously, and the dissipation energy required for failure increases relatively. The two
types of energy are linearly related to the confining pressure. The data are shown in Table 2. With actual engineering, as the ground stress increases, the storage capacity of the rock mass enhances accordingly, and more energy is needed to drive the rock mass to instability and failure.

Figure 17. Relation curve between confining pressure and energy in the triaxial compression test

According to the energy mechanism, the ratio of the dissipation energy to the total input energy \( (E_w) \) is defined as the damage variable \( D \) [29]:

\[
D = \frac{U_d}{U} = \frac{U - U_e}{U}.
\]

When \( D \) is 0, a material is not damaged, and the external input work is transformed into \( E_e \). When \( D \) is 1, a material is completely destroyed, and the bearing capacity is completely lost. The damage variable \( D \) between 0 and 1 indicates that a material is damaged to some extent. The closer \( D \) is to 1, the more serious the material is damaged.

Figure 18 shows the prepeak compression damage curve under different confining pressures. As the loading progresses, the internal microcracks are further initiated, expanded, and condensed. \( D \) increases rapidly, and the rock specimen reaches a critical instability state. Under the same axial strain condition, \( D \) of a low confining pressure is larger than that of a high confining pressure. Under the same damage condition, the specimen with a high confining pressure can bear a large deformation, that is, the specimen with a high confining pressure can restrain damage development. Microscopically, it shows the constraint on the microcrack propagation inside the specimen, and it is macroscopically characterized by the constraint of high pressure on the lateral deformation of the specimen. The residual strength stage retains a certain bearing capacity, so the calculated \( D \) is not 1 at this moment.
3.4. Analysis of crack development

In PFC\textsuperscript{2D} discrete element simulation, cracks can be divided into shear cracks and tensile cracks. Figure 19 shows the evolution curve of the number of total cracks, tensile cracks, and shear cracks as the loading progresses under different confining pressures. At the beginning of loading, the total number of microcracks is almost zero, and the specimen is in an elastic state. As the load increases, the number of microcracks increases gradually, but the growth rate is relatively slow, and the specimen is slightly damaged. When the loading is close to the peak strength, the specimen reaches the plastic stage, the highest crack growth rate is obtained, and a large number of microcracks are initiated and propagated. The specimen becomes damaged and enters the post-peak stage, and the growth rate of the number of cracks gradually slows down. When the specimen is loaded at the residual strength stage, the increase rate of the number of microcracks is low because the microcracks at this stage are mainly generated by friction and sliding between the macrofracture surfaces. The crack growth curve accumulates in an “S” shape, and its abnormal point is consistent with the elastic–plastic characteristic points and instability failure of the stress–strain curve.
In specimen failure, tensile cracks and shear cracks represent different failure mechanisms. In Figure 20, the proportion of tensile cracks and shear cracks varies with confining pressure. When the confining pressures are 0 and 5 MPa, the tension effect is obvious, and the tensile cracks account for 76.1% and 71.3% of the total cracks, respectively. As the confining pressure increases, the proportion of shear cracks increases. When the confining pressure is 15 MPa, the proportion of tensile cracks decreases to 68.2%, and the proportion of shear cracks is 31.8%. When the confining pressure is 25 MPa, the proportion of tensile cracks is further reduced to 64%, and the shear cracks are up to 36% (Table 3). The overall trend indicates that the proportion of shear cracks increases as the confining pressure increases.
### Table 3. Number and proportion of the cracks under different confining pressures

| Confining pressure/MPa | Total number of cracks | Tensile cracks | | Shear cracks |
|------------------------|------------------------|----------------|----------------|----------------|
| 0                      | 2856                   | 2172           | 76.1           | 684            | 23.9           |
| 5                      | 4200                   | 2294           | 71.3           | 1206           | 28.7           |
| 15                     | 5742                   | 3732           | 68.2           | 1740           | 31.8           |
| 25                     | 7200                   | 4608           | 64.0           | 2592           | 36.0           |

### 4. Conclusion

Triaxial compression tests under different confining pressures are conducted to explore the mechanical characteristics of deep-buried rock mass and the inherent mechanism of instability and failure. The analysis combined with the PFC discrete element method is carried out from multiple angles of strength properties, energy field, crack development, damage degree, and other properties, and the main conclusions are as follows.

(1) Under a low confining pressure, the brittleness of the model specimen is obvious, the fracture surface is rough, and the fracture angle is large. As the confining pressure continues to increase, the yield platform of the stress–strain curve becomes more obvious, the dominant fracture surface flattens, and the fracture angle gradually decreases. The confining pressure restrains the occurrence of the local failure of the specimen and causes the specimen to change from local splitting and shear failure under the low confining pressure to overall shear failure under a high confining pressure.

(2) Under a low confining pressure, the crystals on the structure surface are relatively complete, and they are mostly acicular and rod shaped. The local crystal particles are spherical or pie shaped, and the microstructure surface exhibits intergranular tensile failure and partially transgranular shear failure. As the confining pressure increases, the crystal particles become extruded and rub against one another, and a large number of crystal fracture marks appear on the structure surface. The crystals are mostly spherical or pie-shaped structures, and the transgranular shear failure tends to be obvious. As the confining pressure increases, the fractal dimension of the dominant microfracture surface gradually decreases, and the fracture surface changes from a rough and loose crystal tensile–shear failure mode to the relatively flat crystal shear fracture mode.

(3) In the triaxial compression test, energy is stored, dissipated, and released. When the storage limit is reached, the internal elastic strain energy is released rapidly, and the microstructure of the material deteriorates. The damage variable increases quickly, and the external energy input is mainly converted into dissipation energy. As the confining pressure increases, the total energy absorbed by the specimen at the peak point increases continuously, and the dissipation energy required for destruction increases relatively. The two types of energy are linearly related to confining pressure. A high confining pressure can inhibit damage development, which is microscopically shown as the constraint of a high confining pressure on the internal microcrack propagation of the specimen and macroscopically characterized as the constraint on the lateral deformation of the specimen.

(4) As the confining pressure increases, the number of cracks (total cracks, tensile cracks, and shear cracks) accumulates in an “S” shape, and the abnormal change point is consistent with the elastic–plastic characteristic points and failure of the stress–strain curve. Tension cracks and shear cracks are produced during loading, and the proportion of shear cracks gradually increases as the
confining pressure increases.

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