Retraction

Retraction: Energy storage and dissipation characteristics of red sandstone in triaxial compression tests under constant confining pressure (IOP Conf. Ser.: Earth Environ. Sci. 570 032053)

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Energy storage and dissipation characteristics of red sandstone in triaxial compression tests under constant confining pressure

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Abstract. To investigate the energy storage and dissipation characteristics of rock material in triaxial compression tests under constant confining pressure, a series of triaxial single-cyclic loading–unloading compression tests were conducted on red sandstone specimens under eight confining pressures. Using the method of graphic area integration, the input energy density, elastic energy density, and dissipative energy density of the specimen in axial, circumferential, and total directions were obtained. The results indicate that the input energy density in the axial direction accounts for the largest logarithmic proportion of the total input energy density and that the relationship between all the parameters of the energy density and the unloading level can be described by the quadratic function. In the axial direction, a linear function relationship exists among elastic, dissipative, and input energy densities. In the circumferential direction, a quadratic function relationship exists among elastic, dissipative, and input energy densities. For the total energy parameters of the sample, the relationship of elastic, dissipative, and input energy densities conforms to the quadratic function, providing a new method for the accurate estimation of the energy parameters in the rock under high stress.

1. Introduction

Energy conversion is an essential characteristic of material physical processes, which runs through all the stages of rock deformation [1,2]. Thus, energy plays a significant role in rock deformation. Energy storage, dissipation, and release during rock deformation are closely related to the damage state [3,4]. Therefore, studying the internal mechanism of rock deformation from the perspective of energy storage and dissipation is important. To date, numerous attempts related to the energy conversion of rock materials have been made, and some valuable realizations have been achieved. Considering the uniaxial cyclic loading–unloading compression tests, Meng et al. [5,6] studied the characteristics of energy accumulation and dissipation during rock deformation. They implied that with the increase in axial load stress, the total absorbed energy density increased the fastest, followed by the elastic energy density, and the dissipative energy density increased the slowest. Gong et al. [7,8] investigated the energy evolution of red sandstone under different confining pressures and found that a strong linear relationship exists among elastic energy, dissipative energy, and total input energy. Based on the triaxial compression tests, Huang and Li [9] found that the initial confining pressure had a significant influence on the pre-peak conversion rate of dissipative energy and elastic energy. Zhang and Gao [10] investigated the energy evolution of red sandstone under different confining pressures and found that
with the increase in confining pressure, the energy storage limit of rock increased in the form of power index. Although the energy analysis method has been widely applied in the field of rock deformation mechanism and engineering due to its ability to overcome the drawbacks of classical elastoplastic mechanics theory [11,12], studies focusing on the relationship of elastic, dissipative, and input energy densities under triaxial compression are scarce in the aforementioned studies. Zhao et al. [12] indicated that the research on rock energy storage mechanism was insufficient and that improving this study for more experts and scholars was worthwhile. Thus, studying the characteristics of energy storage and dissipation in rock deformation is necessary. Based on the linear energy storage and dissipation law under uniaxial compression, which was proposed by Gong et al. [13], this paper attempts to study the energy storage and dissipation characteristics of red sandstone under triaxial compression.

In this paper, the method of graphic area integration and stress–strain curve were combined to calculate three kinds of the energy density parameters. In addition, the relationship among elastic, dissipative, and input energy densities under different axial or confining pressures in different directions were investigated. The energy storage and dissipation characteristics of red sandstone under triaxial compression were analyzed. The obtained results help us to further understand the energy storage and dissipation laws in triaxial compression tests under constant confining pressure.

2. Experimental study and methods

2.1. Specimen preparation and test equipment

Red sandstone, obtained from the city of Linyi in the Shandong Province, was selected for the laboratory experiments. Cylindrical specimens, which were obtained by core drilling, were utilized in this experiment. The diameter \((D)\) and height \((H)\) of the specimens were 50 and 100 mm, respectively. All rock specimens used for testing are integrated without cracks and exhibit good homogeneity. The sides and the end faces of all rock specimens were smoothly polished, so that the experimental error can be reduced. Meanwhile, the upper and lower end faces of all rock specimens were parallel to meet the standards of the International Society for Rock Mechanics (ISRM) [14]. The experiments were conducted using the MTS 815 electro-hydraulic servocontrolled rock mechanics testing machine, which is presented in Figure 1. The testing machine comprises a loading rack, servo system control box, hydraulic pump, triaxial pressure chamber, and data display screen. In the tests, the axial and circumferential forces of rock specimens were obtained using pressure sensors. Meanwhile, the axial and circumferential strains of rock specimens were measured using the axial and circumferential extensometers, respectively.

![Figure 1. MTS 815 experimental system.](image)

2.2. Test scheme

The triaxial single-cyclic loading–unloading compression (TSCLUC) experiments were conducted under eight confining pressures (5, 10, 15, 20, 30, 40, 50, and 60 MPa) to study the energy storage and dissipation characteristics of red sandstone under triaxial compression. Considering that the loading–unloading paths under each confining pressure are the same, the first experiment, with a confining
pressure of 5 MPa, was adopted to elaborate the experimental procedures. Figure 2 presents the detailed procedures.

First, the forces of axial and circumferential directions were simultaneously applied on the red sandstone specimen at a rate of 0.1 MPa/s. Force application was stopped when the confining pressure reached 5 MPa. Subsequently, all the forces applied to the specimen were decreased to zero at the same rate. Finally, keeping the rock specimen at the confining pressure of 5 MPa, displacement control was adopted to apply load on the rock specimen at a rate of 0.1 mm/min in the axial direction until peak strength. The loading–unloading method for the other seven experiments was the same as that for the first.

Figure 2. Diagram of triaxial loading–unloading segment.

Figure 3. Schematic diagram of the energy density parameters in the axial direction.

2.3. Energy calculation method for the three energy density parameters

According to the first law of thermodynamics, the total input, elastic, and dissipative energy densities of the rock materials in the process of stress and deformation satisfy the following relation [15]:

\[ U = U_e + U_d \]  

where \( U \) denotes the total input energy density produced by the work of the external force; \( U_e \) is the dissipative energy density and used for the internal damage; and \( U_e \) is the elastic energy density stored in the rock unit during the loading–unloading process.

In conventional triaxial compression tests, the stress state changes to biaxial compression, that is, \( \sigma_2 = \sigma_3 \). At this time, the strain energy density absorbed by rock elements can be expressed as

\[ U = \int \sigma_1 d\varepsilon_1 + 2 \int \sigma_2 d\varepsilon_2 \]  

Equation (2) states that the total work of the external force on rock element can be divided into two parts, axial and circumferential, in conventional triaxial compression tests.

Energy density was adopted for all three kinds of energy to eliminate the influence of individual differences of rock specimens on the experiment. The below equations express the interrelation among the three kinds of energy density parameters:

\[ U_i = U_{ae} + U_{ad} \]  
\[ U_i = U_{ai} + U_{ci} \]  
\[ U_{ai} = U_{ai}^A + U_{ai}^C \]  
\[ U_{ci} = U_{ci}^C + U_{ci}^C \] 

where \( U_i \), \( U_{ai} \) and \( U_{ci} \) denote the total input energy density (TIED), total elastic energy density (TEED), and total dissipative energy density (TDED), respectively. \( U_{ai}^A \), \( U_{ai}^C \) and \( U_{ai}^A \) denote the axial input energy density (AIED), axial elastic energy density (AEED), and axial dissipative energy density (ADED), respectively. \( U_{ci}^C \), \( U_{ci}^C \) and \( U_{ci}^C \) denote the circumferential input energy density (CIED),...
circumferential elastic energy density (CEED), and circumferential dissipative energy density (CDED), respectively. \( i_a \), \( i_c \) and \( i \) denote the axial pressure, confining pressure, and stress level, respectively.

Using the method of graphic area integration, the three kinds of the energy density parameters can be obtained. In Figure 3, the schematic diagram of the energy density parameters is presented. The calculation method for the parameters of the circumferential energy density is the same as that for the parameters of the axial energy density. Therefore, taking the axial direction as an example, the AIED value was determined by the area between the initial loading curve and the strain axis. The AEED value was determined by the area between the unloading curve and strain axis. Therefore, the ADED value at the unloading pressure level was determined by the difference between AIED and the corresponding AEED.

3. Stress–strain curves of rock specimens

Under the action of external force, rock undergoes continuous deformation and even failure when the forces reach the failure strength of the rock specimen. In this process, the force and deformation of the rock can be detected by the sensors of the test system. In Figure 4, the stress–strain curves of red sandstone under eight confining pressures are presented. The deformation of red sandstone can be divided into two stages: the initial compaction and elastic deformation stages. In the initial compaction stage, the microcracks and pores in the rock were compacted under the action of external force. At this stage, the rock barely deformed after the removal of the external force. Conversely, in the elastic deformation stage, the microcracks in the rock started to develop. At this stage, the deformation is generally recoverable. Since the rock is not an ideal elastic body, residual deformation occurs after the removal of the external force in the elastic stage. To compare the differences between the circumferential and axial stress–strain curves, the stress–strain curves under the confining pressures of 5 and 10 MPa were enlarged. Figure 4(a) shows that the area enclosed by the initial loading line and unloading line is small when the axial pressures are 5 and 10 MPa. This indicates that in the compaction stage, little energy dissipation occurs. However, as can be observed in Figure 4(b), at the same stress level, the dissipative energy density rapidly increases as the confining pressure in the circumferential direction increases. This demonstrates a greater change in energy than that in the axial direction. This phenomenon was caused by the circumferential surface area of red sandstone specimen being larger. Thus, production of the same deformation requires further work.

![Figure 4](image-url)

**Figure 4.** Stress–strain curves of red sandstone in the TSCLUC tests: (a) axial stress–strain curve and (b) circumferential stress–strain curve.
4. Test Results

4.1. Energy storage and dissipation characteristics of red sandstone in the axial direction

According to the stress–strain curves of the red sandstone specimens, the three energy density parameters in different directions under eight confining pressures were obtained using the method of graphic area integration. In Figure 5, the variation curves of AIED, AEED, and ADED are presented (the coordinate point (0, 0) was adopted to resolve the deviation in Figures 5, 6, 7, 8, 9, and 10). As shown in Figure 5, the three kinds of the energy density parameters increase with the axial pressure, and they all conform to the quadratic function. The growth rate of AIED is greater than that of AEED, and the growth rate of AEED is greater than that of ADED, indicating that the energy storage is greater than the energy dissipation in the axial direction. The growth curve of AEED is close to that of AIED, whereas the growth curve of ADED is far from that of AIED. This indicates that with the increase in axial pressure, the energy storage is dominant in the axial direction. In Figure 6, the relationship among AEED, ADED, and AIED is presented. The figure shows that AEED and ADED linearly increase with AIED, which have correlation coefficients of 0.9989 and 0.9800, respectively. This shows that under triaxial compression, the energy storage and dissipation characteristics of red sandstone are linear in the axial direction, which is in accordance with the finding of Gong et al. [13] under uniaxial compression.

4.2. Energy storage and dissipation characteristics of red sandstone in the circumferential direction

As can be seen from Figure 7, the variation curves of CIED, CEED, and CDED under eight confining pressures conform to the quadratic function. However, CIED, CEED, and CDED differ from AIED, AEED, and ADED in terms of the variation trend. Under the initial confining pressure, CDED is greater than CEED. When the confining pressure exceeds 50 MPa, CEED becomes greater than CDED. This indicates that the confining pressure of 50 MPa is the turning point of the energy from dissipation to accumulation in the circumferential direction. Figure 8 presents the relationships among CEED, CDED, and CIED. CEED and CDED exponentially increase with CIED, and their correlation coefficients are greater than 0.99, indicating a very strong correlation. As shown in Figure 7, the circumferential energy density variation characteristics indicate that energy dissipation is dominant in the circumferential direction when the confining pressure is less than 50 MPa.
4.3. Energy storage and dissipation characteristics of red sandstone in the total direction

Figure 7 presents the variation trend of the three energy density parameters in the total direction. With the increase in the stress level, TIED, whose correlation coefficient is 0.9963, increasingly conforms to the quadratic function. TEED and TDED also conform to the relationship, and their correlation coefficients are 0.9968 and 0.9888, respectively. However, in the initial stress level, TDED is higher than TEED. When the stress level exceeds 20 MPa, TDED becomes lower than TEED. This phenomenon is caused by the level of increase of TDED being greater than that of TEED in the initial stress level. Figure 8 presents the quadratic function relationships between TEED and TDED, with the increase in TIED in the total direction. This provides a new method for the accurate estimation of the energy parameters of red sandstone under high stress.

5. Discussion

Although rock is an inhomogeneous material with joints and fissures, a certain regularity of energy transformation is present under triaxial compression. In the axial direction, a good linear relationship exists among AEED, ADED, and AIED, which is consistent with the findings of Gong et al. [13] under uniaxial compression. In the circumferential direction, a quadratic relationship exists among CEED, CDED, and CIED, and the circumferential energy dissipation is greater than the circumferential energy storage when confining pressure is less than 50 MPa. Due to the influence of circumferential energy transformation, TEED and TDED have a quadratic relationship with TIED. This provides a method for the accurate estimation of the energy density parameters in the red sandstone under high stress. In subsequent studies, more loading-unloading compression tests will be conducted to further investigate the energy storage and dissipation characteristics of red sandstone under triaxial compression.

6. Conclusions

A series of TSCLUC experiments of red sandstone under eight confining pressures were conducted. The method of graphic area integration was used for calculating the energy density parameters in
different directions. The relationships among elastic, dissipative, and input energy densities under different axial or confining pressures were analyzed. The conclusions can be derived as follows. A strong linear relationship exists among the axial elastic, dissipative, and input energy densities under triaxial compression. Energy storage is dominant in the axial direction. Moreover, the circumferential elastic and dissipative energy densities have a quadratic function relationship with the circumferential input energy density under triaxial compression. Similar to the circumferential direction, the relationship among the total elastic, dissipative, and input energy densities presents a strong quadratic function relationship. This provides a new method for the accurate estimation of the energy parameters in the rock under high stress. In the total direction, energy storage plays a significant role.

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