Research Article

Experimental Study on Mechanical and Acoustic Emission Characteristics of Rock Samples under Different Stress Paths

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A series of tests on characteristics of acoustic emission have been performed on sandstone under uniaxial, conventional, and triaxial conditions and the unloading confining pressure path. The failure mode of rock specimen has been scanned by CT and a three-dimensional reconstruction was made. The differences on characteristics of AE, mechanics, and the failure mode of sandstone during the failure process under three paths are studied. The results show that the deformation of rock specimen is bigger, and axial strain and circumferential strain have a deformation platform at peak point of stress under the unloading confining pressure path. Characteristics of AE ringing are significantly affected by the confining pressure and stress path. AE ringing counts peak value, and accumulative ringing on the breaking moment as well as cumulative release energy is higher, which indicates that the rock failure is more violent under the unloading confining pressure path. The failure mode of rock specimen was dominated by shear failure under the conventional triaxial stress path. The tension failure is the main form at a lower initial value of unloading confining pressure, and the shear failure is more prominent at a higher initial value of unloading confining pressure.

1. Introduction

During the excavation in underground projects of deep rock, rock masses have been subjected to the stage of loading-unloading repeatedly before the excavation and the condition of unloading after the excavation. That is, rock masses have experienced the mining process from stress of the primary rock, increasing load, and unloading to failure. The stress path is different from unloading and loading, and mechanical properties and the fracture mechanism have both similarities and differences. Safety of the excavation in underground projects is attracting more attention. The study of damage formation in jointed or bulk rock under stress has been a subject of widespread interest, and the results have led to a number of comprehensive texts. Acoustic emission (AE) techniques are broadly applied to rock in order to obtain information on the crack initiation and propagation in rock engineering [1–3].

There are a large number of research results about acoustic emission in the process of rock loading, including uniaxial loading, conventional triaxial loading, unloading confining pressure, and cyclic unloading. The study on acoustic emission characteristics of coal rock has been finished, and the relationship between acoustic emission characteristic parameters and the rock loading failure process has been obtained by the acoustic emission test under uniaxial compression [3–5]. The variant trends are identical between ringing counting and accumulative energy with acoustic emission experiments of the rock damage process under different confining pressures [6, 7]. Acoustic emission events are fewer before yield and gradually become more active during the period of postyield, and then the AE cumulative count and the cumulative number of energy have the singular points obviously in the case of the stress peak [8, 9]. The characteristics of AE are analyzed under the unloading confining pressure, and then the failure characteristics and the mechanism of rock burst

FIGURE 1: The rock servo-controlled rheology testing machine.

are discussed with the granite unloading confining pressure test on acoustic emission under different loading paths [7, 10–13].

There are a lot of research results about the failure process of rock acoustic emission under the loading path, but comparative analyses are not enough on the mechanical properties, acoustic emission characteristics, and failure modes under the paths of uniaxial loading, regular triaxial loading, and unloading confining pressure. Thus, the analysis research has been completed about the mechanical properties and acoustic emission characteristics of rock under different loading paths in this paper. Then, the macroscopic failure morphology is analyzed through the CT scanning and the 3D image reconstruction. A basis for understanding the fracture mechanism of rock materials will be provided by the research results.

2. Experimental Processes

In accordance with the test requirements of International Institute of Rock Mechanics, the sandstone samples were processed into standard specimens with a diameter of 50 mm and a height of 100 mm. Test specimens with a wave velocity of about 2000 m/s are screened using the test system of Sonic Viewer-SX rock sample to reduce the discreteness of the specimen.

The loading device adopted the automatic servo rheometer of TOP INDUSTRIE Rock 600-50 (Figure 1), which was composed of servo devices of axial pressure, confining pressure, and seepage pressure. The axial strain was monitored by 2 linear displacement sensors (LVDT). The circumferential strain was monitored by the electronic strain gauge which was placed at the height of the center. Acoustic emission information was collected by Acoustic Emission System of SH-II. Acoustic emission sensors were arranged on outside and below the three-axle chamber. The sampling frequency of acoustic emission was 2.5 MHz, and the gain and the threshold value were 40 dB and 30 dB, respectively.

The sandstone samples were performed by three loading paths, namely, uniaxial compression, the conventional triaxial compression, and unloading confining pressure.

Path 1 is uniaxial compression loading. The samples were loaded to destroy completely by the displacement-controlled method. The axial loading rate was 0.1 mm/min. Three rock

TABLE 1: Experiment results of rock specimens under different stress paths.

Serial number	Density g/cm ³	$\sigma_1 - \sigma_3$ /MPa	σ_3 /MPa (initial)	σ_3 /MPa (destroy)
D ₀₋₂	2.10	62.6	0	0
S ₅₋₂	2.10	121.6	5	5
S ₁₀₋₁	2.10	145.6	10	10
S ₁₅₋₃	2.09	178.5	15	15
S ₂₀₋₃	2.12	202.4	20	20
X ₅₋₁	2.10	96.8	5	4.2
X ₁₀₋₂	2.10	119.1	10	5.9
X ₁₅₋₃	2.10	144.6	15	12.4
X ₂₀₋₂	2.10	160.6	20	13.4

samples were repeated, which were numbered D0-1, D0-2, and D0-3, respectively.

Path 2 is conventional triaxial compression. First, the samples were loaded in the hydrostatic pressure condition ($\sigma_1 = \sigma_2 = \sigma_3$) at the loading rate of 0.05 MPa/s. Then, the specimens were loaded to destroy completely at the axial loading rate of 0.1 mm/min. The confining pressures were 5 MPa, 10 MPa, 15 MPa, and 20 MPa, respectively, and three samples in each condition were repeated, which were numbered S₅₋₁, S₅₋₂, S₅₋₃, S₁₀₋₁, S₁₀₋₂, S₁₀₋₃, S₁₅₋₁, S₁₅₋₂, S₁₅₋₃, S₂₀₋₁, S₂₀₋₂, and S₂₀₋₃, respectively.

Path 3 is unloading confining pressure. First, the samples were loaded in the hydrostatic pressure condition ($\sigma_1 = \sigma_2 = \sigma_3$) at the loading rate of 0.05 MPa/s. Then, the specimens were loaded under about 80% of the ultimate stress at the axial loading rate of 0.1 mm/min. Last, the confining pressure of specimens was unloaded at the axial loading rate of 0.05 MPa/s, in the condition of keeping the main stress constant. The specimens were loaded to destroy completely at the axial loading rate of 0.1 mm/min when destroyed. The initial values of the unloading confining pressure were 5 MPa, 10 MPa, 15 MPa, and 20 MPa, respectively, and three samples in each condition were repeated, which were numbered X₅₋₁, X₅₋₂, X₅₋₃, X₁₀₋₁, X₁₀₋₂, X₁₀₋₃, X₁₅₋₁, X₁₅₋₂, X₁₅₋₃, X₂₀₋₁, X₂₀₋₂, and X₂₀₋₃, respectively.

3. The Characteristics of Sandstone of Strength and the Deformation under Different Stress Paths

The rock specimens under different stress paths were analyzed, whose strength was close to the average strength under the different conditions. The rock specimens selected were D₀₋₂, S₅₋₂, S₁₀₋₁, S₁₅₋₃, S₂₀₋₃, X₅₋₁, X₁₀₋₂, X₁₅₋₃, and X₂₀₋₂. The test results are shown in Table 1.

3.1. Mechanical Properties of Sandstone under the Paths of Uniaxial and Conventional Triaxial Compression. The stress-strain curves were shown in Figure 2 under the paths of uniaxial and conventional triaxial compression.

FIGURE 2: Complete stress-strain curves of rock samples under uniaxial and triaxial compression.

(1) Under the different confining pressures, the stress-strain curve of the compression test shows four stages of the rock deformation: the initial compaction phase, elastic stage, plastic stage, and postpeak stage. Sandstone samples had the confining pressure effect obviously. Under the condition of triaxial compression, the initial compaction phase was not obvious, compared with the uniaxial compression test. The main reasons are that the original crack was compacted; the compaction stage was not obvious; the internal original crack of the rock sample was compacted under the condition of hydrostatic pressure. Besides, the compressive strength and the elastic limit of the rock sample became larger with the increase of confining pressure.

(2) Under the condition of triaxial compression, the rock sample still had a certain bearing capacity when it apparently exhibited a macrocrack. When the confining pressures were 5 MPa, 10 MPa, 15 MPa, and 20 MPa, residual strength of rock samples were 55 MPa, 96 MPa, 110 MPa, and 120 MPa, respectively. Because the high confining pressure limited the damage of rock, the plastic deformation and the peak strain of rock increased, and the failure mode of rock gradually transformed into a progressive failure.

3.2. Mechanical Properties of Sandstone under the Unloading Confining Pressure Path. Under different initial confining pressures, the curves of the stress-strain test are shown in Figure 3. Under the unloading confining pressure path, the prepeak deformation characteristics were approximately the same, and the peak deformation was different from those of the conventional three-axis tests. Under the confining pressure path, when the stress reached the peak strength, the decrease of the confining pressure would make the lateral slip of rock fractures increase, and the plastic deformation of circumference would increase. There was an obvious deformation yielding platform for the circumferential strain and volume strain.

FIGURE 3: Stress-strain curves of rock samples under unloading confining pressure.

FIGURE 4: Stress-strain curves of axial and circumferential under different initial confining pressures.

Under the unloading confining pressure path, the clear sound for rupture occurred when rocks were broken. The bearing capacity of rocks lost suddenly after rocks were broken, and the residual strength of rocks became smaller. When the value of σ_1 remained unchanged and σ_3 kept decreasing, the rock was very prone to a sudden failure, leading to the rock burst, such as the wall rock of the underground excavation.

Under different confining pressures, the curves of axial strain and circumferential strain are shown in Figure 4. Under the unloading confining pressure, axial strain was larger, and the axial strain became greater with the confining pressure increasing. The circumferential strain was limited by the confining pressure, and the circumferential strain became smaller with the confining pressure increasing. At the initial stage of the unloading confining pressure, the growth rate of the circumferential strain was much higher than that of the

FIGURE 5: Axial strain and circumferential strains of stress peak value under different stress paths.

axial strain. Both the axial strains and circumferential strains were approximately linear related to the confining pressure. The rock samples were in the elastic deformation stage. The rock samples came into the plastic deformation stage with the confining pressure unloaded step by step, and the rates of the axial and circumferential strains increased obviously. In this stage, the circumferential strains increased more sharply, and the circumferential deformation took the dominant position of the rock deformation.

Under different stress paths, the axial and circumferential strains corresponding to the peak stress are shown in Figure 5 (the circumferential strain in the graph is absolute). As seen from the trend line in the chart, the axial and circumferential strains are much less than the conventional triaxial compression path, and its deformation is characterized as the transition from being ductile to being brittle.

Rock mechanical properties under different stress paths correspond to the different states in underground excavation engineering. The changes of mining load will lead to different axial and lateral deformations, and the influences of unloading confining pressure path are more remarkable about the rock deformation, which shows that the rock in the unloading pressure state is more likely to destroy under smaller deformation conditions, and the deformation characteristics of the rock under the unloading pressure condition should be paid more attention with the depth of rock underground engineering increasing.

4. Analysis of Rock Acoustic Emission Characteristics and Failure Modes under Different Stress Paths

AE information can reflect the fracture damage of the rock, which is closely related to the evolution of the primary fissures as well as the initiation, propagation, and coalescence of new fractures in the process of rock loaded. In this paper, the ringing count and ringing accumulation numbers of acoustic emission were measured to analyze acoustic emission

FIGURE 6: Test results of AE ringing counts of rock specimens under uniaxial compression.

characteristics of the rock failure process under different loading paths. The morphology of the rock failure was scanned by the CT system with a microfocus microscope, and the three-dimensional shape of the rock failure was reconstructed by the three-dimensional and visual modeling software.

4.1. Analysis of Acoustic Emission and the Destruction Process of Rocks. In the time-domain graph of the acoustic emission wave, the output of a pulse is called AE ringing with transducer in each shock. By contrasting counting characteristics of acoustic emission in different processes of a rock failure, the following conclusions are obtained.

(1) Under the uniaxial compression test, the time-stress-ringing curve of the rock failure process is shown in Figure 6. During the compaction stage, a certain amount of acoustic emission events occurred, and most of them were with small scales. The acoustic emission ring count was low. At the elastic deformation stage, the acoustic emission ringing counts decreased gradually. Following the plastic deformation stage, ringing counts gradually increased with the initiation and propagation of the main fracture. During the last stage of the plastic deformation, the ringing count peaks were centrally active, which could be regarded as forthcoming peak stress of the rock samples. At the peak point of stress, the rock samples underwent a suddenly brittle failure and lost their carrying capacity after the failure, and the acoustic emission events suddenly became silent.

(2) Under the triaxial compression test, the time-stress-ringing curves of the rock failure process are shown in Figure 7. In the early stage of loading, acoustic emission rarely occurred, because a large number of primary pores in the rock had been tightly closed during the application of hydrostatic pressure, and the integrity and stiffness of the rock had increased. During the elastic deformation stage, the acoustic emission ringing counts were relatively inactive, and the values of ringing counts were small; in addition, the duration time of this stage became longer with the confining pressure increasing. Following the plastic deformation stage, rock particles and fractures slip were limited by the confining pressure, which improved the shear strength of the rock. The active degree of AE count has decreased obviously compared

FIGURE 7: Test results of AE ringing counts of rock specimens under different confining pressures.

with the uniaxial compression path, and the active stage of peak value was not obvious. At the loading stage of postpeak, the rock samples still had a certain residual strength because of the confining pressure, and microcracks of rocks continued to emerge and expand after the main fault occurring. At this stage, acoustic emission was more active, and the crack initiation and propagation occurred obviously accompanied by a sudden increase of AE counts. That is, the peak counts of acoustic emission have a good relationship with the stress drop.

Compared with the postpeak stage of different confining pressures, acoustic emission became less active with the increase of the confining pressure, which was due to the crack initiation and propagation limited by the high confining pressure. It can be seen from the CT scanning and 3D reconstruction images that the sandstone under the triaxial compression path was a mainly shear failure, and the fracture of specimens was accompanied by more macroscopic cracks at a low confining pressure. However, the macrocrack decreased obviously under the high confining pressure, which explains the phenomenon that the ringing number of acoustic emission was weakened at the high confining pressure.

(3) Under the unloading confining pressures test, the time-stress-ringing curves of the rock failure process are shown in Figure 8. Before the failure of rock samples, the AE signal was not obvious under the confining pressure, and the ring count of acoustic emission was relatively low, which

was closer to the prepeak stage of the triaxial compression loading. With the confining pressure unloaded, the rock samples lost the confining pressure, and the rocks were damaged suddenly when the pressure reached rock bearing limit, which was accompanied by a great deal of elastic energy suddenly releasing and the ringing number of AE sharply increasing. After a sudden brittle fracture, the rock samples lost their carrying capacity and had almost no residual strength. The ring count of acoustic emission became suddenly silent, and the postdestruction stage was closer to the postpeak stage of uniaxial loading.

The confining pressures were 4.2 MPa, 5.9 MPa, 12.4 MPa, and 13.4 MPa, and the failure modes included tensile failure, tensile failure, tensile shear failure, and shear failure, respectively, at the peak damage when the initial values of unloading confining pressures were 5 MPa, 10 MPa, 15 MPa, and 20 MPa. That is to say, the tensile failure was dominant at the low initial value of the unloading confining pressure, and the shear failure was predominant at the high initial value of the unloading confining pressure.

From the analysis of the failure mechanism of rocks, under the condition of σ_1 remaining unchanged and $\sigma_1 - \sigma_3$ increasing, microcracks were arranged in the direction of the maximum principal stress due to axial stress at the initial stage of the unloading confining pressure. With confining pressure unloaded further and $\sigma_1 - \sigma_3$ increasing gradually, the microcracks were compressed along the direction of maximum principal stress and the tension cracks were expanded

FIGURE 8: Test results of AE ringing counts of rock specimens under the unloading confining pressure.

continuously. This conforms to the Griffith failure criterion. When the confining pressure was unloaded to a certain extent, the tensile stress of the end crack was concentrated, which is due to the rebound deformation caused by pressure unloaded. And, tensile cracks may be connected, and then the failure mode of tensile splitting was formed at a low confining pressure. During the test of this study, the rate of confining pressure unloaded was 0.05 MPa/s, a lower rate. Therefore, the confining pressure remained at a relatively high degree during the formation of the main fracture, which limited the rate of the lateral deformation. As a result, the rock samples were still subjected to a shear failure at the high initial confining pressure.

4.2. Analysis of Acoustic Emission Ringing Cumulative Number. The cumulative number of AE rings reflects the variation of cumulative damage during the rock failure. Due to limited length of this article, only the tests of the uniaxial, conventional triaxial compression ($\sigma_3 = 20$ MPa) and the unloading confining pressure (initial values of the confining pressure σ_3 is 20 MPa) were listed in this paper. The curves of time-stress-cumulative number of rings are shown in Figure 9 during the process of the rock failure. The main conclusions are obtained by the comparison with the number of rings accumulated under different loading paths.

(1) Under the uniaxial compression path, the curve of cumulative number of rings could be divided into 3 stages: the initial growth stage, the stable growth stage, and the rapid

growth stage. There was no obvious quiet period in the whole loading process.

(2) Under the conventional triaxial compression path, the curve of cumulative number of rings could be divided into 3 stages: the quiet stage, the sudden increase stage, and the postpeak unstable stage. Due to the effects of the confining pressure, there was an obvious quiet period in the curve of cumulative number of rings, and the longer the confining pressure lasted for, the longer the stationary phase lasted. During the postpeak stage, each apparent stress drop was accompanied by a sudden increase in the cumulative number of AE rings.

(3) Under the unloading confining pressure path, the curve of cumulative number of rings had obvious stages of a calm and sudden increase. There was a sudden failure in the peak, and no instable stage in the postpeak.

4.3. Analysis of AE Characteristics and Failure Modes under Different Stress Paths. (1) Under the paths of conventional triaxial compression and unloading compression, AE counts had no obvious active stage compared with the uniaxial test in the latter stage of the plastic deformation.

The rock specimens were destroyed suddenly under the paths of uniaxial and unloading compression, and AE was not obvious in the postpeak stage. What is more, during the postpeak stage of the conventional triaxial compression path, the residual strength of rock samples remained under the action of the confining pressure, and there were strong

FIGURE 9: Test results of AE accumulative ringing of rock specimens under different stress paths.

acoustic emission signals due to the friction of the crack growth and the fracture surfaces.

Under conventional triaxial compression paths and unloading confining pressure paths, the peak curves of acoustic emission count are shown in Figure 10. Under the unloading confining pressure path, the ring count peak of rock samples was obviously larger than those of conventional triaxial compression paths. The main causes were sudden and strong brittle fractures of rock specimens under the unloading confining pressure paths. When the rock samples failed, the release of elastic energy was more concentrated and a larger scale of fractures was produced.

In order to analyze the influences of the confining pressure during a rock failure, a cumulative number of moments ringing were analyzed under different stress conditions. Trend lines of AE accumulative ringing of rock specimens on the breaking moment are shown in Figure 11. Under the unloading confining pressure path, the cumulative number of AE ringing was larger than those of conventional triaxial compression paths. The main causes are that a larger scale of fractures of rock specimens was produced and the moment accumulated damage was also greater during the rock breaking because of the elastic energy sudden release.

FIGURE 10: Peak value of AE ringing counts under different stress paths.

From the macroscopic failure morphology of rock samples, a shear failure of sandstone was dominated under the

FIGURE 11: The trend line of AE accumulative ringing of rock specimens on the breaking moment.

conventional triaxial compression path, and there were both a tensile failure and a shear failure under the unloading confining pressure path. Under the unloading confining pressure path, the number and size of macrocracks increased obviously comparing with the conventional triaxial compression path after the rock failure.

5. Conclusion

In this paper, a series of tests on characteristics of acoustic emission have been performed on sandstone under different stress paths, and the failure modes of rock specimens have been scanned by the CT after the rock destroy. The differences in characteristics of AE, mechanics and failure modes of sandstone during the failure process under three paths were studied. The main conclusions are as follows.

(1) Under different stress paths, the deformations of sandstone samples have significant differences. Under the unloading confining pressure path, the circumferential and volumetric deformations have more obvious influences on the rock. Under the confining pressure path, the decrease of the confining pressure makes the lateral slip of rock fractures increase, and there are obviously deformation yielding platforms for the circumferential strain and volume strain at the peak point.

(2) Under the unloading confining pressure path, the axial strain and the hoop strain are smaller than those of the conventional triaxial compression path, and under the unloading state of the underground excavation, the rock is more likely to be destroyed by smaller deformation conditions. With the depth of rock underground engineering increasing, the deformation characteristics of the rock should be paid more attention under the unloading condition.

(3) Under the uniaxial loading path, acoustic emission is produced significantly in the compaction stage. Under the conventional triaxial compression path, AE signal is not obvious due to the primary pores of the rock closed by hydrostatic pressure, and the sudden increasing phenomenon of AE ringing is weakening with initiation and propagation

of the crack limited by the high confining pressure. Under the unloading confining pressure path, rock specimens are destroyed suddenly and strongly due to elastic energy releasing intensely, and the peak and accumulated number of AE ringing are greater than those of the conventional triaxial compression path.

(4) Under conventional triaxial compression path, the shear failure of sandstone is dominated, and there are both a tensile failure and a shear failure under the unloading confining pressure path. Under the conventional triaxial compression path, the initiation and propagation of microcracks are inhibited by the confining pressure, and the number of macroscopic cracks produced under a low confining pressure is much higher than those of a high confining pressure. Under the unloading confining pressure path, the rebound deformation caused by the unloading confining pressure makes the tensile stress concentrated and expanded at the end of the tension crack. Then the tensile fracture may be interconnected directly under a low confining pressure, and the tensile splitting failure mode will be formed. In the case of the high initial confining pressure, the concentrated level of tensile stress will be weakened. The rate of the lateral deformation was limited by the high confining pressure, and a shear failure still occurs in rock samples.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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