Deformation and Acoustic Emission Characteristics of Cracked Granite during Creep

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A series of multistage creep tests under different confining pressures with acoustic emission monitoring have been performed to investigate the deformation characteristic and failure process of cracked granite during creep. The critical axial strain of cracked sample showed an increasing tendency with the increase of confining pressure. In contrast, critical lateral strain experienced a process of descending first at low confinement and then remaining nearly constant at high confinement. Compared with loading-cracked specimen, smaller critical axial strain, greater critical lateral strain, and higher lateral creep strain rate were found for unloading-cracked specimen. Based on the spatial and temporal distribution of acoustic emission events, the cracking process during creep was analysed. The AE events with high energy are mainly concentrated at the final fracture area of the specimen. The higher the confining pressure, the more the AE events with low energy. Compared with the loading-cracked specimen, the percentage of AE events with high energy is relatively small for the unloading-cracked specimen.

1. Introduction

In many instances of geotechnical projects, the deformation failures and losses of stability are not instantaneous but develop over time [1–4]. The time-dependent failure of rock tunnels in underground engineering can occur after construction for many years. Therefore, the creep (time-dependent) behavior of rocks, which refers to the continued deformation under constant stress, including deformations, failures, and slips, is increasingly considered. The creep behavior of surrounding rock is of special interest for underground repositories for high-level radioactive waste (HLW). The research on the delayed mechanical behavior of surrounding rock is of important significance for predicting the long-term stability of HLW repository in two periods, i.e., the life period of the underground storage (about 100 years) and the period during which the wastes should be confined (many thousands of years) [5].

Extensive laboratory tests on creep behavior of rocks have been conducted around the mid of last century. In early studies, the majority of the creep tests were performed for a period of less than a week, under uniaxial compression and at room temperature [6–8]. As the time-dependent behavior of rocks is increasingly considered, numerous experiments have been carried out considering the effects of deviatoric stress [9, 10], confining pressure [11–13], temperature [5, 14], structural anisotropy [15, 16], and so on. These studies mainly focus on the intact rock samples.

However, the creep along preexisting joints or bedding plan is also important [17]. Wawersik [18] and Solberg et al. [19] carried out a series of triaxial tests to study the creep in deep seated fracturess and faults. Uniaxial tests were conducted on jointed samples to investigate the influence of shear stress on the creep behavior of artificial cohesive and noncohesive joints [20, 21]. According to the results of investigations, the creep behavior of jointed sample shows the same character as that of the intact rock [18, 22]. However, the strain of the jointed sample is somewhat larger than that of intact rock. Hamza and Stace [23] investigated...
the creep behavior of intact and fractured rock samples. A larger creep deformation, larger steady-state creep rate, and smaller creep parameters were found for the fractured rock.

In China, a deep granite formation located in the Beishan region of Gansu Province of northwestern China is considered as a possible host medium for HLW storage [24]. A series of creep tests on intact samples were carried out to investigate the influence of temperature and stress condition on the creep behavior of Beishan granite [25]. Considering that the time-dependent behavior of cracked rock represents an important condition of rock mass [23], the objective of the experiments in this study is to investigate the creep characteristics of cracked Beishan granite. A series of multistage creep tests under different confining pressures were conducted on cracked rock. The acoustic emission monitoring technique is used to understand the failure process during creep.

2. Laboratory Investigation

2.1. Materials and Apparatus. The granite in the laboratory experiments was obtained from borehole B806 of Beishan area located in Gansu Province of northeastern China. The sampling depth was from 450 to 600 m below the ground surface. The rock can be classified as fine-medium-grained and has a dry density of 2.7 g/cm³. Cylindrical dry samples of 100 mm in height and 50 mm in diameter were prepared following the procedures outlined in Standard for Test Method of Engineering Rock Mass (GB/T50266-2013) [26].

The laboratory tests were conducted with the MTS815 rock mechanics test system. The equipment is characterized by its high measuring accuracy, high rigidity, and stable performance and reliability, with a maximum axial loading capacity of 4600 kN and a maximum confining pressure capacity of 140 MPa. Meanwhile, a 3D acoustic emission (AE) system was employed to monitor the microcracking process inside rock specimen in real time.

2.2. Test Method and Procedure. 8 samples were adopted in this study. Each specimen was used to carry out three types of tests: loading (specimen number: L1 to L4) or unloading (specimen number: U1 to U4) test on intact rock, triaxial compression test on cracked rock, and creep test on cracked rock. The stress conditions of each test were shown in Table 1.

Two types of cracked rock samples, namely, loading-cracked and unloading-cracked samples were produced from the intact rock samples after bringing them to failure in loading or unloading test. The loading test is a conventional triaxial compression test with the prescribed confining pressure \( \sigma_3 \) (ranging between 0.2 and 15 MPa), which is also the same confining pressure in the following triaxial compression test and creep test on loading-cracked samples. In unloading test, the confining pressure is first loaded to the initial level (30, 40, 50, and 60 MPa) at a constant loading rate of 3 MPa/min. Then loading axial force and unloading confining pressure are performed simultaneously at a constant loading rate of 48 kN/min and a constant unloading rate of 3 MPa/min. When the stress level approaches the peak value, the axial loading mode is transformed into lateral deformation control mode at a constant rate of 0.02 mm/min until the residual stress stage is reached. Then unload the axial pressure to 2 kN at a rate of 30 kN/min, and keep the confining pressure constant until the end of the creep test.

In the triaxial compression tests on cracked samples, the axial stress is applied by the lateral deformation control mode at a constant rate of 0.02 mm/min. When the stress level is not increased with the increase of deformation, the axial force is unloaded to 2 kN at a rate of 30 kN/min. The main purpose of this test is to determine the compressive strength of these cracked samples and guide the following creep tests.

At last, the creep tests on cracked samples are carried out by a stress-stepping loading mode. The axial stress is increased stepwise at a certain percentage of the compressive strength \( \sigma_{cr} \) determined from the above triaxial compression test on cracked sample, about 50%, 60%, 70%, and 80% for the first 4 stages. The loading time of each stage is about 10 h. If the creep failure does not occur at the stress stage of 80%, the axial stress will be increased to a higher level (90% of the compressive strength or even more) and remain constant until rock failure.

2.3. Loading-Cracked and Unloading-Cracked Samples. In this study, the cracked samples are obtained from the intact rock samples after bringing them to failure in loading or unloading test. Figure 1 shows the variation of axial and lateral strain with confining pressures in loading and unloading tests. When the intact granite fails, the axial strains \( \sigma_1 \) in both loading and unloading tests are found to be higher than lateral strains \( \sigma_3 \). Under the same confining pressure, the axial strain in unloading test is much lower than that in loading test. However, a slightly higher lateral strain is observed in unloading test than in loading test. Since the rock failure is essentially related to the cracking process inside rock specimen, this result indicates the difference of the initial state of the cracks inside the loading-cracked samples and unloading-cracked samples.

Based on the triaxial compression test on cracked samples, the compressive strength of the cracked sample at the given confining pressure is determined, which provides the guidance for the following creep test. Since the short-term deformation and strength characteristics of cracked rock are not included in this study, there is not much discussion of the mechanical properties of cracked rock in this study.

3. Experimental Results of Creep Test

Figure 2 shows results of multistage creep tests conducted on loading-cracked and unloading-cracked samples at different confining pressures. The most noticeable finding is that all strain curves in axial and lateral direction typically show the three phases on the figure: transient creep phase, steady-state creep phase, and accelerated or tertiary creep phase. It can also be noticed that the lateral strain is much more evident and larger than the axial strain under the same deviatoric stress.
3.1. Critical Strain of Creep Failure. Figure 3 shows the cracked specimens’ creep curves at the last stage of multistage creep test. The transformation process from the steady-state creep phase to accelerated creep phase can be observed clearly. The strain rate is nearly constant in the steady-state creep phase and is generally identified as the creep strain rate. When the microcracks inside the specimen accumulate to a certain extent, the creep enters the accelerated creep phase, and the deformation and strain rate increase rapidly. As a result, the creep failure occurs soon. In this regard, the critical state of entering the accelerated creep phase and the corresponding strain can be viewed as the critical state and critical strain of creep failure.

Table 1: Stress conditions and loading path of each test.

| Experimental type                  | Stress condition (MPa)                          | Specimen number |
|------------------------------------|------------------------------------------------|-----------------|
| Loading or unloading test on intact rock | Initial confining pressure: 0.2 2 5 15 30 | L1  L2  L3  L4  U1  U2  U3  U4 |
|                                    | Confining pressure at rock failure: 0.2 2 5 15 6.34 |               |
|                                    | Confining pressure at residual stress stage: 0.2 2 5 15 2.38 |               |
| Triaxial compression test on cracked rock | Confining pressure: 0.2 2 5 15 2.38 4.86 10.12 19.17 |               |
| Creep test on cracked rock         | Deviatoric stress at different loading stages: |               |
|                                    | 1 80.12 81.43 54.20 109.47 95.80 74.40 77.10 140.10 |               |
|                                    | 2 96.14 97.72 65.05 131.37 114.90 89.30 92.50 168.10 |               |
|                                    | 3 112.16 114.01 75.88 153.26 134.10 104.20 107.90 196.20 |               |
|                                    | 4 128.19 130.29 97.56 175.16 153.20 119.10 123.30 224.20 |               |
|                                    | 5 — 145.52 104.26 189.87 175.50 134.20 138.90 252.80 |               |
|                                    | 6 — — — 197.51 — 141.70 146.50 — |               |

Figure 1: Variation of axial and lateral strain in loading and unloading tests.

Figure 2: Variation of axial strain and lateral strain of cracked rock in creep tests. (a) Loading-cracked samples. (b) Unloading-cracked samples.
The variation of critical axial and lateral strain of creep failure with confining pressure is presented in Figure 4. From Figure 4(a), the critical axial strain shows an increasing tendency with the increase of confining pressure, for the loading-cracked specimen or unloading-cracked specimen. At the same confining pressure, the critical axial strain of loading-cracked specimen is greater. For the critical lateral strain (Figure 4(b)), it experiences a process of descending first at low confinement and then remaining nearly constant at high confinement. Unlike the critical axial strain, the critical lateral strain of the unloading-cracked specimen is greater than that of the loading-cracked specimen at the same confining pressure.
Compared with the loading-cracked specimen, a smaller critical axial strain and greater critical lateral strain are observed for the unloading-cracked specimen. This result of cracked specimen in creep test is in accordance with the strain state of intact specimen after loading and unloading tests. The cracked specimen in this study is produced after bringing the intact sample to failure in loading or unloading test. Compared with the loading test, a smaller axial strain and greater lateral strain in unloading test are observed at the failure of intact sample (Figure 1). The strain state at rock failure in loading and unloading tests represents the initial state of the cracks inside the cracked specimen to some extent. That is, the triaxial compression test and creep test on cracked sample may lead to the propagation of the micro-cracks and also the consistent change in axial and lateral strain of loading-cracked and unloading-cracked samples.

3.2. Creep Deformation Characteristics. Based on the creep curves presented in Figure 2, the transient creep phase and steady-state creep phase can be observed in each stage of the multistage creep test. The creep strain in one stage can be viewed as the sum of strain values of the transient creep phase and steady-state creep phase. The sum of creep strain in each stage is the creep strain of the specimen. To investigate the creep deformation characteristics, the ratio of creep strain to total strain (critical strain of creep failure) is calculated, which reflects the importance of creep deformation in total deformation. Figure 5 shows the variation of this ratio with confining pressure. It is noticed that, at different confining pressures, the cracked (loading-cracked and unloading-cracked) specimen has a similar ratio in the axial direction, about 10%. The ratio in lateral direction is relatively higher than that in axial direction. Furthermore, the higher the confining pressure, the lower the ratio in the lateral direction. With the increase of confining pressure, the decreasing tendency of the ratio of the unloading-cracked specimen is not obvious, and the average ratio is about 55%. For the loading-cracked specimen, the ratio is decreased from 72% at the confinement of 0.2 MPa to 55% at the confinement of 15 MPa. That is, for the loading-cracked specimen in lateral direction, the contribution of creep deformation to total deformation is decreased with the increase of confining pressure. This result reflects the confinement effect of confining pressure on creep deformation in the lateral direction.

3.3. Creep Strain Rate. Considering that the creep deformation in lateral direction is greater and more noticeable, the creep strain rate in lateral direction calculated from each steady-state creep phase is discussed in this section. The creep strain rates of cracked specimens at similar confining pressure are plotted in one figure, such as loading-cracked specimen L2 and unloading-cracked specimen U1 in Figure 6(a) and loading-cracked specimen L3 and unloading-cracked specimen U2 in Figure 6(b). As the axial stress was increased stepwise at a certain percentage of the compressive strength ($\sigma_{cf}$), the abscissa of Figure 6 is the percentage. It is noticed that increasing the axial stress level can result in a greater lateral creep strain rate. Under the confining pressure of 2 MPa, the cracked specimens fail at the loading stage of $90\%\sigma_{cf}$, with the lateral creep strain rates of 0.0128%/h for the loading-cracked specimen and 0.0404%/h for the unloading-cracked specimen. However, under the confining pressure of 5 MPa, the lateral creep strain rate of the cracked specimen at the loading stage of $90\%\sigma_{cf}$ is about
0.0024%/h. The cracked specimens fail at the loading stage of 95%σ_{cf}, with the lateral creep strain rates of 0.2364%/h for the loading-cracked specimen and 0.4377%/h for the unloading-cracked specimen. Overall, the lateral creep strain rate of the unloading-cracked specimen is slightly higher than that of the loading-cracked specimen, especially on the condition of high axial stress. On the same condition of axial stress, the lateral creep strain rate at high confinement is lower than that at low confinement.

### 4. Acoustic Emission Characteristics

As a viable nondestructive monitoring method, the acoustic emission technique is usually used in laboratory test to monitor the microcracking process of rocks. In this study, a 3D acoustic emission is employed during the experiment. Figures 7–9 show the AE spatial distribution and failure pattern of cracked specimens during multistage creep test. It can be noticed that, regardless of the magnitude of applied confining stress, the recorded AE events are relatively limited and widely distributed inside the specimen at the low stress stages. With the increase of axial stress and damage accumulation inside the specimen, a large amount of AE events is recorded at the last stage of creep failure, and the AE events are observed to accumulate in some areas. At high confinement, the specimen is mainly subjected to shear failure. The AE events are concentrated along a slanted plane, which is consistent with the final failure pattern presented in Figure 7(b). At low confinement, the tensile-shear mixed mode fracture is the most common failure form of granite (Figures 8(c) and 9(c)). For unloading-cracked specimen (Figure 9(c)), the tensile fracture dominates and the tensile crack is the major type of crack. The amount of AE events at the last stage of creep failure is enormous due to
the numerous microcracks inside the specimen. In order to investigate the AE distribution characteristics, the AE events with amplitude $>45$ dB of loading-cracked and unloading-cracked specimens are presented in Figures 8(b) and 9(b), respectively. It can be noticed that the most high amplitude cracks occur at the location of final fracture area. The most widely distributed and highest number of AE events is that with small amplitude corresponding to the microcracks inside the specimen. The higher amplitude corresponds to the higher energy of the recorded AE event. On this basis, the AE events at the stage of creep failure, especially with high energy, are mainly concentrated at the final fracture area.

Figure 10 shows the AE characteristics of cracked specimen during multistage creep test. At low axial stress stages, only the transient creep phase and steady-state creep phase can be observed, and the AE energy rate is at a lower level. As presented in the magnified image in Figure 10(a), the AE energy rate in the transient creep phase is relatively higher than that in the steady-state creep phase. During the
steady-state creep phase, the AE signal is more stable and some AE events with high energy are observed sometimes. With the increase of axial stress, a large number of AE events with high energy are recorded, especially at the last stage of creep failure. Accordingly, a sharp increase in cumulative AE counts is observed. Furthermore, the rapid increase in cumulative AE counts occurs before the appearance of the large increase in axial strain, which makes the AE technique be a good tool for monitoring the stability of underground engineering.

Figures 10(e) and 10(f) show the distribution percentage of the AE energy rate of loading-cracked and unloading-cracked specimens, respectively. The chart shows clearly that the AE energy rate dominates in the range of 0–5. The percentage is up to 65% for the loading-cracked specimen at the confinement of 15 MPa and 85% for the unloading-cracked specimen at the confinement of 19.17 MPa. The higher the confining pressure, the more AE events with low energy (energy rate is in the range of 0–5) and consequently the less AE events with high energy (energy rate >20). It could be attributed to the confinement effect of confining pressure on creep deformation. With the increase of confining pressure, the brittle-ductile transition of deformation takes place. The energy of the AE events induced by the ductile deformation is relatively lower, as presented in Figures 10(b) and 10(d).

For the loading-cracked and unloading-cracked specimen, in the energy rate range of 0–5, the percentages are 39% (specimen L2) and 64% (specimen U1) at the similar confinement of 2 MPa and 49% (specimen L3) and 66% (specimen...
U2) at the similar confinement of 5 MPa. That is, the percentage of AE events with low energy of the unloading-cracked specimen is much higher than that of the loading-cracked specimen. Accordingly, compared with the loading-cracked specimen, the percentage of AE events with high energy is relatively small for the unloading-cracked specimen.

5. Discussion

Different from the evident creep phenomenon of soft rocks such as rock salt, sandstone, and clay, the creep deformation of brittle rock such as granite is relatively small. In this study, the creep tests were conducted on cracked granitic samples, which were produced from the intact rock samples after bringing them to failure in loading or unloading test. Although there are many microcracks inside the specimen, the cracked specimen is still a whole system due to the confinement effect of confining pressure. Accordingly, the creep phenomenon of the cracked specimen is a complicated compound pattern, including the creep properties of granite rock and microcracks.

According to the experiment results, when the stress level is lower than 80% of the compressive strength \(\sigma_{cf}\) of cracked specimen \(\sigma_{cr} = 0.2\) MPa \(L1, \sigma_{3} = 2.38\) MPa. (b) Specimen \(U4, \sigma_{3} = 19.17\) MPa. (c) Specimen \(L2, \sigma_{3} = 2\) MPa. (d) Specimen \(L4, \sigma_{3} = 15\) MPa. (e) Energy distribution (loading-cracked). (f) Energy distribution (unloading-cracked).

Figure 10: AE characteristics of cracked specimen during creep test.
AE events are relatively limited and widely distributed inside the specimen (Figures 7–10). In this situation, the structure appears to be stable but still has microcracks inside and it is difficult to tell what dominates the creep phenomenon of the cracked specimen. However, when the stress level exceeds a certain threshold (80% $\sigma_{cr}$ or 90% $\sigma_{cr}$ in this study), the creep enters the accelerated creep phase, and the deformation (Figure 3) and strain rate (Figure 6) increase rapidly. A large amount of AE events induced by microcracks is recorded in this stage (Figures 7–10). The structure becomes unstable and fails finally due to the initiation and accumulation of new microcracks and the extension and slippage of existing microcracks. At this stage, the creep phenomenon is dominated by plastic deformation. In addition, the confining pressure and the initial state of the cracks before the creep test may have important effects on the creep phenomenon of cracked rock, and we will put more effort in this problem in the future.

6. Conclusions
The main goal of this work is to investigate the creep behavior of cracked granite under multistage stresses. Two types of cracked specimens, namely, loading-cracked and unloading-cracked specimens, were adopted. In particular, a 3D acoustic emission test system was employed to monitor the microcracking process inside the specimen. The main conclusions are drawn as follows:

(1) The creep strain of the cracked specimen under different confining pressures is much more evident and larger in the lateral direction than in the axial direction. Within the tested range of confining pressures, the critical axial strain of creep failure shows an increasing tendency with the increase of confining pressure. However, for the critical lateral strain of creep failure, it experiences a process of descending first at low confinement and then remaining nearly constant at high confinement. Compared with the loading-cracked specimen, a smaller critical axial strain and a greater critical lateral strain are observed for unloading-cracked specimen.

(2) Within the tested range of confining pressures, the ratio of creep strain to total strain in axial direction is similar and about 10%. In lateral direction, the decreasing tendency of the ratio of the unloading-cracked specimen is not obvious, and the average ratio is about 55%. However, for the loading-cracked specimen, an appreciable decline in the ratio is observed, from 72% at the confinement of 0.2 MPa to 55% at the confinement of 15 MPa. A possible explanation for this might be that the confinement plays an important role in closing up the microcracks inside the specimen and stabilizing the cracked specimens.

(3) The lateral creep strain rate of the unloading-cracked specimen is slightly higher than that of the loading-cracked specimen, especially on the condition of high axial stress. On the same condition of axial stress, the lateral creep strain rate at high confinement is lower than that at low confinement.

(4) At low axial stress stages, the AE energy rate is at a lower level, and it is relatively higher in the transient creep phase than in the steady-state creep phase. With the increase of axial stress, a large number of AE events with high energy are recorded, especially at the last stage of creep failure. The AE events with high energy are mainly concentrated at the final fracture area of specimen.

(5) The higher the confining pressure, the more AE events with low energy and consequently the less AE events with high energy. Compared with loading-cracked specimen, the percentage of AE events with high energy is relatively small for the unloading-cracked specimen.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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