Effect of stress condition on the creep behaviour of Beishan granite

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Abstract. In China, a deep granite formation in Beishan area is currently considered as a potential host rock for high-level radioactive waste repositories. Creep tests were conducted by two modes, namely single step loading mode on several samples and multi-step loading mode on single sample. According to the experiment results, the granite specimens failed almost at the same axial strain and volumetric strain at a given confining pressure, despite of the differences in deviatoric stress, stress ratio or strain ratio. The increase in stress condition (deviatoric stress, stress ratio, or strain ratio) could accelerate the cracking process and creep strain rate, and consequently resulted in a shorter time to failure. The stress effect on the cracking process was also confirmed by the acoustic emission (AE) energy rate. Significant increases in AE energy rate and the percentage of AE events with high energy could be observed with the increase of deviatoric stress. It was indicated from the results that, the stress ratio and strain ratio were more reasonable when discussing the influence of stress condition, perhaps because they were defined by considering both the applied stress level and the mechanical properties of rock material.

1. Introduction
Deep geological disposal is worldwide considered as an acceptable option to deal with the high-level radioactive waste (HLW). The deep geological disposal facility is designed to be situated many hundreds of meters underground. The conceptual design of repositories generally relies on a multi-barrier system, which typically comprises of the natural geological barrier and an engineered barrier system. The geological environment (the natural barrier system) in HLW disposal includes the rock formation which hosts the disposal tunnels, other rock formation which surrounds the host formation, and whose behaviour affects the performance of underground repository [1]. The host rock (including granite, salt, tuff and clay) is served as the last natural geological barrier to isolate the long-lived radionuclide from biosphere. Consequently, the knowledge of the geological and geographical setting and detailed understanding of the host rock are essential to the long-term stability and safety of the HLW disposal project [1-2]. As one of the most important mechanical properties of rock material, the creep behaviour of rock is considered an important basis for explaining and analyzing the phenomena of geological tectonic movements, especially for predicting the long-term stability of rock engineering [3-7]. In HLW disposal, it may take a long period (hundreds of thousand years) for the long-lived radionuclide to decay to a level that poses no significant risk to human beings [2]. Thus, the long-term stability and safety of the geological disposal facility within a geological environment must be insured.
Accordingly, it is necessary to explore the creep (time-dependent) behaviour of host rock. During the construction of the geological disposal facility, the excavation will disturb the original in-situ stress field and lead to stress redistribution around the excavation. Due to the long-term effect of the environmental stress, the microcracks inside the rock may be initiated and propagated during the creep process of host rock, which may lead to the degradation of the mechanical and hydraulic properties of host rock. Moreover, the microcracks may serve as the potential pathways of nuclide migration, and consequently, affect the geological environment tremendously. Therefore, a good understanding of the effect of stress condition on the creep properties is essential.

In China, a deep granite formation in Beishan area located in Gansu Province of north-western China is currently considered as a potential host rock for HLW repositories [8]. Symmetrical investigations of the geological, hydrogeological environment and mechanical behaviour of host rock have been systematically conducted [9-10]. However, some key problems like the threshold stress level of Beishan granite and the effect of stress condition on the creep behaviour still have not been properly understood. In this study, we therefore perform a series of creep tests at different stress conditions to verify the effect of stress on the creep properties. In view of the fact that differences in mineral components and homogeneity of specimens may have an influence on the creep response of rock, the creep tests in this study are conducted by two modes, namely single step loading mode on several samples and multi-step loading mode on a single sample. Moreover, two factors related with stress condition, namely stress ratio and strain ratio are defined by considering both the applied stress effect and the mechanical properties (crack damage stress and the corresponding volumetric strain) of specimen to analyse the effect of stress condition. A three-dimension acoustic emission (AE) test system is employed to capture the microcracking process during creep process.

2. Experimental investigation

2.1. Sample preparation

The granite samples studied in this work are prepared from a massive intact granite block taken from a shallow depth in Jijicao subarea of Beishan site, which can be classified as fine-grained biotite monzonitic granite. The rock is mainly composed of approximately 33.65% plagioclase, 31.1% quartz, 13.55% alkali feldspar, 20.05% mica, and 1.65% clay minerals [11]. The specimens used in the laboratory investigation are cored to be 100 mm in length and 50 mm in diameter following the Standard for Test Method of Engineering Rock Mass [12]. The grain density is 2.615 g/cm$^3$ and the average P-wave velocity is 3364 m/s.

2.2. Testing facilities and procedure

Creep tests were carried out using a MTS815 rock mechanics test system. In creep experiment, the test consists of two stages: initial loading stage and constant stress loading stage (figure 1). In the initial displacement loading stage, the test was carried out under a constant lateral strain rate of 0.0038%/min. When the deviatoric stress was achieved to the predetermined stress level, the control mode was changed to stress control mode and the deviatoric stress was maintained at a constant level. In order to make the failure of specimen occur in a short time, the constant stress level was predetermined higher than the crack damage stress defined as the stress at the point of volumetric strain reversal, which marks the onset of unstable crack growth and may related to the long-term strength [13].

In analysing the effect of stress condition on the creep properties of rocks, the stress level in constant stress loading stage is usually used as an evaluation factor. However, due to the variations of mineral components and homogeneity of specimens, the mechanical property (such as crack damage stress) of specimen may be different. Consequently, the effective stress condition applied on rock specimens induced by the same stress level may be different. In view of this, another two factors associated with the internal mechanical properties of rock specimens, i.e., stress ratio $\beta$ and strain ratio $\alpha$ are also used in this study to evaluate the effect of stress condition. According to the study by Martin and Chandler [21], the specimen starts to dilate and the cracking process becomes unstable once the stress level surpasses the crack damage stress. Accordingly, the crack damage stress is widely considered as related to the long-term strength of rock material. The crack damage stress $\sigma_{cd}$ is defined
as the stress at the point of volumetric strain reversal in the initial loading stage (figure 1). The corresponding volumetric strain is \( \varepsilon_{cd} \). As presented in figure 1, the stress ratio \( \beta \) is defined as the ratio of the applied deviatoric stress \( \sigma \) to the crack damage stress \( \sigma_{cd} \) (\( \beta = \sigma / \sigma_{cd} \)). The strain ratio \( \alpha \) is defined as the ratio of \( (\varepsilon_{cd} - \varepsilon_0) / \varepsilon_{cd} \) (\( \alpha = (\varepsilon_{cd} - \varepsilon_0) / \varepsilon_{cd} \)), and \( \varepsilon_0 \) is the volumetric strain when the creep test enters into the constant stress loading stage.

Before the creep test, the stress ratio \( \beta \) is predetermined in the range of 1.30 to 1.41. According to the definition of the stress ratio \( \beta \), the target stress level in constant stress loading stage should be \( \beta\sigma_{cd} \), and the crack damage stress \( \sigma_{cd} \) can be obtained from the stress-strain curve in the initial loading stage. The creep tests were conducted by two modes, namely single step loading mode on several samples and multi-step loading mode on a single sample. In single step creep test, the stress was kept constant until the rock failure. In multi-step creep test, the axial stress was increased in steps by increasing the stress ratio 0.01 per step. At each loading step, the deviatoric stress was kept constant for a time interval of more than 4 hours with the steady state strain rate calculated. If no rock failure occurred after the loading of one step, then the stress ratio \( \beta \) was increased to the next until the rock failure.

Table 1 shows the stress conditions and experimental results of the creep tests. All creep tests were conducted at room temperature (23°C) with a same confining pressure of 2 MPa.
3. Experimental results

3.1. Effect on creep rate and time to failure

Results from the creep experiments under different stress conditions are shown in figure 2. In each case, the axial strain and volumetric strain clearly exhibit the type of trimodal behaviour that characterizes brittle creep deformation. The creep deformation can be characterized by three stages: primary (or transient), secondary (or steady state), and tertiary (or accelerated) creep stages. The granite specimens under different stress conditions (single step creep tests or multi-step creep tests) are found to fail almost at the same axial strain and volumetric strain, which are defined as the critical axial strain and critical volumetric strain of creep failure respectively. It is indicated that the critical cracking state of creep failure cannot be changed by the variation of stress condition and loading history (stress loading mode), since the microcracking and crack propagation should be responsible for the deformation and failure of brittle rock. Under the confining pressure of 2MPa, the Beishan granite failed at a similar strain of about 1.6% for volumetric strain and 0.42% for axial strain. Considering that the volumetric strain reflects both the axial strain and lateral strain, and the change in pore volume caused by crack, the creep study in this context is mainly focused on the evolution of volumetric strain.

Figure 3(a) shows the evolution of strain rate during the creep process, which is the first derivative of the volumetric strain-time curve. Considering that the applied stress level is higher than the crack damage stress, the rock’s volumetric strain during creep decreases monotonically with time, as presented in figure 2. Hence, the volumetric strain rate should be always negative. In this work, the key thing we are focused on is the magnitude of the volumetric strain rate and its variation tendency during creep. Therefore, the volumetric strain rates presented in figure 3 are absolute values. The strain rate decreases gradually in the transient creep stage, and increases abruptly in the accelerated creep stage that ultimately leads to the rock failure in figure 3(a). There is an extended period of constant strain rate between the transient creep stage and accelerated creep stage. The strain rate in secondary creep stage is thereafter referred to as the steady state strain rate. The variation of steady state strain rate and time to failure under different stress conditions are shown in figure 3(b), (c) and (d). It can be noticed that small changes in deviatoric stress $\sigma$, stress ratio $\beta$ or strain ratio $\alpha$ result in very large changes in both the strain rate and time-to-failure.

In figure 3(b), the steady state strain rate shows an increasing tendency with increasing deviatoric stress in multi-step creep test. However, when creep tests are conducted on different rock specimens (single step creep test), the variation of steady state strain rate is irregular. This result may be attributed to the difference in mechanical properties (such as crack damage stress) of specimens. In
table 1, a slight difference in crack damage stress for different rock specimens can be observed, such as 108.45MPa for specimen A-3 and 98.58MPa for specimen A-4. In view that the crack damage stress is widely considered as related to the long-term strength of rock and the cracks inside specimen became unstable when the stress level surpasses the crack damage stress, specimen A-3 is supposed to be stronger than A-4. Compared with the 133.08MPa applied on specimen A-4, the stress level of 144.24MPa applied on specimen A-3 may not lead to the increase in stress condition, but the decrease in stress condition. It can be reflected by the decrease of stress ratio $\beta$ from 1.35 to 1.33 and strain ratio $\alpha$ from 1.19 to 0.72, which ultimately leads to the decrease in strain rate and the increase in time-to-failure. Based on the discussion above, the constant stress level should not be only considered to study the effect of stress condition on creep behaviour when creep tests are conducted on different rock specimens. The stress ratio and strain ratio are defined by considering both the applied stress effect and the mechanical properties (crack damage stress and the corresponding volumetric strain) of specimen, which makes them more reasonable when it comes to discuss the influence of stress condition. From figure 3 (c) and (d), increasing the stress ratio or strain ratio results in an increase in steady state strain rate and consequent a decrease in time to failure.

**Figure 3.** Plots of volumetric strain rate and time to failure at different stress conditions.

As for application, the strain ratio $\alpha$ is found to be more feasible than the stress ratio $\beta$ to characterize the effect of stress condition. During the initial loading stage, a small increment in deviatoric stress usually leads to a great increase in volumetric strain when the stress level surpasses the crack damage stress (figure 1 (a)). Therefore, the increase in strain ratio is more apparent than the increase in stress ratio with increasing deviatoric stress.

3.2. **Acoustic emission characteristics**

The detected AE singles give a better understanding of the cracking process during the creep test. Figure 4 shows the variation of volumetric strain, the cumulative AE counts and cumulative AE energy during the creep tests. It is noticed that both the cumulative AE counts and cumulative AE energy follow the same evolution trend as volumetric strain. However, the AE activity is found to be more sensitive to the occurrence of rock failure than the rock deformation. That is, before the occurrence of the accelerating increase in volumetric strain, a sharp increase in cumulative AE counts or cumulative AE energy has been detected.
Furthermore, the stress effect on the cracking process during creep is also confirmed by the AE energy rate. Since the AE activity is in connection with the initiation and propagation of microcracks inside the rock specimen and the failure mode of the specimen, the disturbance caused by the variation of rock specimens may be more obvious when considering the effect of stress condition on AE activity. Therefore, based on the multi-step creep test conducted on a single specimen, the effect of deviatoric stress has been discussed. The evolution of AE energy rate and percentage of AE energy are illustrated in figure 5. Similar to volumetric strain rate, an increase in AE energy rate can be observed with the increase of deviatoric stress. In addition, the percentage of AE events with high energy (energy ≥ 10) is also increased with increasing deviatoric stress. According to the AE spatial distribution and failure pattern of rock specimen presented in figure 6, it is interesting to notice that those AE events with high energy are mainly concentrated along the failure surface which is consistent with the final failure pattern of specimen. However, the concentration along the failure surface is not apparent at the beginning of creep process. From figure 7 (a) (the AE spatial distribution at different creep stages), the AE events with high energy are relatively limited and widely distributed inside the specimen at the transient creep stage. On the contrary, the percentage of AE events with low energy (energy < 3) is high (figure 7 (b)). With the propagation of microcracks and accumulation of damage inside the specimen, a large amount of AE events with high energy are detected along a single plane in the last two creep stages. In particular, the percentage of AE events with energy ≥ 10 in the accelerated stage has more than doubled comparing with that in transient stage.

Figure 4. Plots of volumetric strain and cumulative AE counts or energy against time.

Figure 5. AE characteristics at different deviatoric stresses (A-5).
4. Discussion

From table 1, it can be noticed that the steady state volumetric strain rate in multi-step creep test is much lower than that in single step creep test when the same stress ratio $\beta$ or strain ratio $\alpha$ is conducted. For example, the stress ratios during the creep process of specimen A-3 and in the fourth step of specimen A-5 are both 1.33. However, the steady state volumetric strain rate of A-3 is 0.37%/h, which is much higher than that of specimen A-5 (0.021%/h). This difference may be relevant to the multiple loading histories in multi-step creep test. Comparing with the 0.19 hours of the initial loading time of specimen A-3, the stress loading time before the stage of $\beta=1.33$ is about 27 hours for specimen A-5. This situation of using a longer time to get the same stress ratio can be regarded as a decrease in stress loading rate. However, experimental investigation [14] on the influence of loading rate on mechanical behaviours of rock materials indicated that, the loading rate could result in the change of rock rupture shape. Increase of loading rate makes the rock breaking into pieces and increases energy loss. In this review, due to the faster loading rate of A-3 before the stress ratio stage of 1.33, the cracking state inside the specimen of A-3 is more unstable than A-5. Therefore, when a same constant loading stress is reloaded, a faster cracking and a higher volumetric strain rate of A-3 are noticed.

5. Conclusions

In this study, the influence of stress condition on the creep behaviour of Beishan granite is investigated with the help of MTS815 rock mechanics test system and 3D AE monitoring system. Essential conclusions are drawn as follows:

(1) The granite specimens under different stress conditions (single step creep tests or multi-step creep tests) are found to fail almost at the same axial strain and volumetric strain, which are about 1.6% for volumetric strain and 0.42% for axial strain at confining pressure of 2MPa. The critical strain of creep failure may provide a reference for the long-term stability analysis of a HLW repository.

(2) Overall, increasing the deviatoric stress $\sigma$, stress ratio $\beta$ or strain ratio $\alpha$ can result in an increase in steady state strain rate and consequent a decrease in time to failure. Comparing with deviatoric
stress, the stress ratio and strain ratio are more reasonable when it comes to discuss the influence of stress condition, especially for the creep tests conducted on different rock specimens.

3) The stress effect on the cracking process during creep is also confirmed by the AE energy rate. Significant increases in AE energy rate and the percentage of AE events with high energy can be observed with the increase of deviatoric stress. In accelerated creep stage, the percentage of AE events with energy ≥ 10 has more than doubled comparing with that in transient stage.

These findings may be somewhat limited by the range of stress level; nevertheless the findings have important implications for setting up a new framework for investigating the time-dependent behaviour of rocks on the basis of their short-term properties. A number of possible studies on Beishan granite using similar experimental approach with a wider range of deviatoric stress (between crack initiation stress and crack damage stress) will be performed in the future. A natural progression of these laboratory tests is to establish a creep constitutive model which is capable of reproducing the full creep in granite under different stress conditions, and implement the results into numerical modelling commercial package for the long-term stability analysis of a HLW repository. Furthermore, the time-dependent behaviour of fractured rock represents an important condition of rock mass, and numerous possible future studies on fractured granite are apparent.

6. References
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