International Journal of Rock Mechanics & Mining Sciences 71 (2014) 340–349

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Characterization of damage evolution in granite under compressive stress condition and its effect on permeability

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ARTICLE INFO

Article history:
Received 16 July 2013
Received in revised form
24 July 2014
Accepted 31 July 2014
Available online 7 September 2014

Keywords:
Damage evolution
Acoustic emission
Permeability
Beishan granite

ABSTRACT

With the aid of 3D acoustic emission (AE) monitoring system, the cracking process of granite under compressive stress condition and its effect on the hydro-mechanical properties is experimentally studied. The granite is taken from Beishan area, a preferable region for high-level radioactive waste (HLW) disposal in China. The experiment results suggest that the rock failure and degradation of mechanical properties are essentially related to the propagation and coalescence of induced cracks. Using an anisotropic damage tensor proposed by Shao et al., the damage evolution during the whole loading process is studied according to the experimental data. It is revealed that the damage evolution is mainly initiated with the appearance of nonlinear mechanical behaviour, and accelerated close to the failure point and in post-peak region. The estimated damage variable in lateral direction is found be globally higher than the value in vertical direction. The recorded AE events indicate that cracking process of granite could be accelerated due to the existence of hydraulic pressure. As a result, much lower compressive strength is obtained under same effective confining pressure in hydro-mechanical coupling tests. A similar tendency of damage and permeability is noticed, and the permeability variation in granite is found to be negligible before the coalescence of microcracks. Finally, an empirical relation is proposed to describe the influence of damage evolution and confining pressure on permeability variation.

1. Introduction

Deep geological disposal is widely considered as the most suitable option to deal with the high-level radioactive waste (HLW), which is generally based on a multiple-barriers system concept. As the last barrier to the biosphere, the host rock plays a critical role to ensure the stability and safety of the repository project. For the HLW repository, the initiation and propagation of the excavation damaged zone (EDZ) in surrounding rock may not only lead to the degradation of mechanical and hydraulic properties of host rock, moreover it may serve as the potential pathways of nuclide migration. Therefore, the damage evolution and its impact to permeability of rock mass are of wide interest in the physical–mechanical investigations of host rock for HLW disposal project, particularly to the brittle rocks like granite in which the cracks do not have the self-sealing capacity.

Numerous studies have been reported on the initiation and growth of microcracks as well as its effect on material behaviors [1–4]. It is verified that microcracking process under compressive stress condition is related to several mechanisms, including the sliding along pre-existing microcracks and gain boundaries, pore crushing, elastic mismatch between mineral grains and dislocation movement [5]. In brittle rocks like granite, the rock failure and nonlinear mechanical behavior are mainly caused by the propagation and coalescence of microcracks [6]. Furthermore, as a consequence of the appearance and growth of cracks, the permeability of rock mass can be significantly increased [7–9], particularly in the post-peak region. Based on the experimental data, some relationships between the macroscopic mechanical behaviors like volumetric deformation with permeability of damaged rock are established [10–14]. In these studies, the emphasis was mainly put on macroscopic hydro-mechanical performance of damaged rock. However, due to the limitation of experimental techniques, few attentions have been paid on the physical mechanism of damage evolution and its effect on the hydro-mechanical properties under different stress condition.

In recent years, the acoustic emission (AE) technique provides an ideal non-destructive method for studying crack growth (damage) at its actual state, which is based on the recording of transient elastic wave resulting from the sudden energy release due to microcracks [15–18]. In this study, with a three-dimension acoustic emission (AE) test system and an optimized permeability test method, it is intended to characterize the damage evolution process of granite

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http://dx.doi.org/10.1016/j.ijrmms.2014.07.020
1365-1609/

under compressive stress condition, and to study its effect on the mechanical and hydraulic properties of damaged rock. The granite is taken for Beishan site, which is currently considered as the most potential area for China's HLW repository. In the paper, using the experimental data and an anisotropic damage tensor proposed by Shao et al. [6], the damage evolution of granite under compressive stress condition and its effect on the hydro-mechanical behavior were discussed.

2. Design of the experimental tests

2.1. Sample preparation

In China, the Beishan region located in northwest China is currently considered as the most potential area for the HLW disposal. Up to now, nineteen deep boreholes (600 m) have been drilled within the potential area, and systematical investigations of the geological, hydrogeological environment were conducted [19]. The granite samples used in the laboratory test were taken from the borehole BS06 of Beishan site at depth of 450–550 m. The granite can be classified as fine-grained granodiorite, and is relatively isotropic in texture and composition with low porosity (0.29–0.32%). The average grain density is 2.71 g/cm^3 and the natural density is about 2.64 g/cm^3. The granite was mainly composed of approximately 52% plagioclase, 17% quartz, 15% alkalifeldspar, 12% biotite, 3% albite, and <1% myrmekite. Specimens were prepared following the Standard for Test Method of Engineering Rock Mass in China (GB/T 50266-2013) [20], with the dimension of Φ50 mm × H100 mm.

In the seepage experiment of low permeable rock like granite, the permeability variation of rock specimen cannot be detected in case the induced fracture doesn't cross over the two surfaces of rock specimen. In experimental studies, a macroscopic fracture is always formed in advance by shearing or compressing at low confining pressure [21]. However, these pre-produced fractures are not identical with fractures induced under the actual stress conditions. Therefore, the representativeness of the results obtained with this method is doubtable. In our study, to ensure the connectivity between the induced fractures of different failure mode and two surfaces of specimen, two holes with a dimension of Φ5 mm × H80 mm are drilled in rock specimens, as presented in Fig. 1.

2.2. Testing facilities

The mechanical and permeability tests were conducted in Sichuan University in China with the MTS815 rock mechanics test system with a maximum axial loading capacity of 4600 kN. Two linear variable differential transducers and an axial extensometer (-2.5–5 mm) are used to measure the axial deformation, while the circumferential deformation is measured by an extensometer (-2.5–8 mm).

Meanwhile, a 3D acoustic emission system (Model: PCI-2) is used to record the cracking process. In the test, eight sensors were attached to specimen to obtain the spatial distribution of AE events, and the sampling rate was 40 m/s. The used AE sensors are Mic30 sensors with a central frequency of 300 kHz, and a frequency range from 150 kHz to 1000 kHz. The preamplifier gain is 40 dB, and the threshold is fixed at 30 dB. The average compressive wave velocity is about 5200 m/s (range: 5120–5351 m/s).

2.3. Test method and procedure

In the study, both traditional uniaxial/triaxial mechanical compression test and hydro-mechanical coupling test are performed to have a comprehensive understanding of hydro-mechanical coupling behavior of Beishan granite. It should be mentioned here that the cracking process is quite different under tensile and compressive stress condition [22,23]. In this study, the attention is mainly paid on the mechanical behavior of Beishan granite under compressive stress condition.

2.3.1. Mechanical test

According to the field measurement in the deep boreholes in Beishan area, the recorded stress value within target disposal depth range (400–600 m) varies from 15 MPa to 27 MPa. Considering the surrounding rock is submitted to quite low confinement due to the release of stress after excavation, the compressive mechanical test was performed at different confinements (0 MPa, 2 MPa, 10 MPa, 15 MPa, 20 MPa, 30 MPa and 40 MPa). In the test, after confining pressure is applied with a loading rate of 3 MPa/min, the specimen is firstly axially loaded at a rate of 30 kN/min. Then, when the axial stress approaches the failure strength, a constant lateral deformation rate of 0.02 mm/min is maintained to avoid rock burst at failure point.

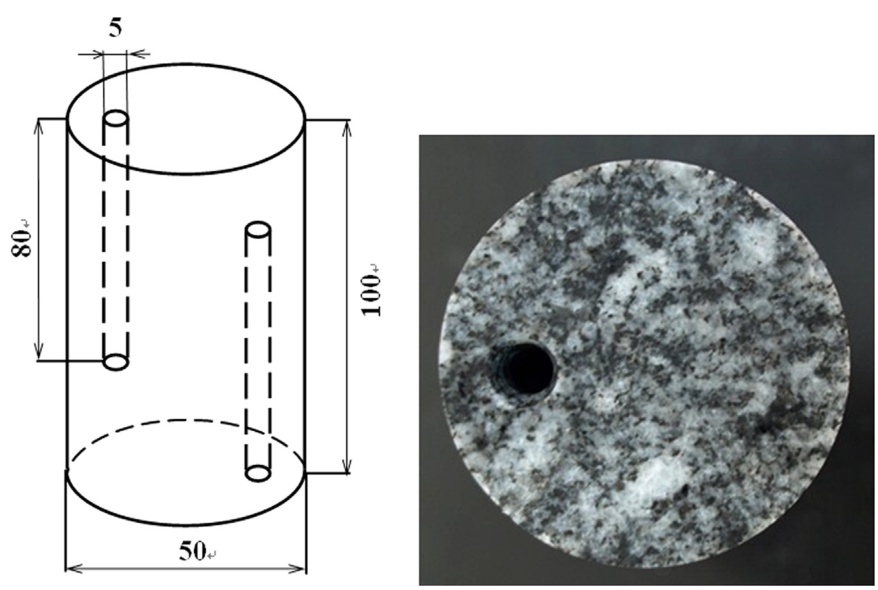

Fig. 1. Rock sample preparation (mm) for permeability test.