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Effects of temperature and stress on the time-dependent behavior of Beishan granite

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A R T I C L E I N F O

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1. Introduction

Deep geological disposal is worldwide considered as an acceptable option to deal with the high-level radioactive waste (HLW). According to this concept, two time periods are of interest: (1) the life period of the nuclear waste repository, during which the repository is under operation (about 100 years); and (2) the period during which the long-lived radionuclide should be isolated from biosphere until it has decayed to a level that poses no significant risk to human beings (hundreds of thousand years).[1] Due to the heat generated by the nuclide decay, an increase of temperature in surrounding rock will be resulted which may lead to the degradation of the physic-mechanical behavior of rock mass. Thus, a good understanding of the time-dependent behavior of host rock under repository condition is essential to the long-term stability and safety analysis of the repository.

Because the time-dependent behavior of brittle rock is generally considered to be negligible in conventional underground engineering, the existing studies are mainly focus on the soft rocks like clayey, sandstone and salt.[1–4] Only few publications about brittle rock can be found in the literature. In these works, the macroscopic creep behavior,[5,6] the cracking process[7,8] and time-dependent failure mechanism[8–10] of brittle rock have been studied. It is revealed that the time-dependent strain of brittle rock under constant loading is typically composed of three phases: primary, secondary and tertiary phases. The initiation and propagation of microcracks are uniform during the first two phases, and have little tendency to link. At the tertiary phase, the cracking process will be accelerated once the crack process reaches a critical state, and ultimately results in the rock failure. Some studies on the long-term behavior of brittle rock in the intermediate temperature range were conducted which is of great interest to the geological disposal. It is indicated that the increase of temperature within 200 °C may significantly weaken the rock and reduce the time to failure.[11,12] However, some key problems like the temperature and stress effect on the time-dependent strength, the cracking process and the critical cracking state to failure have not been properly understood, and the long-term behavior of brittle rock under repository condition still remains a topic largely open.

In China, a deep granite formation in Beishan area located in Gansu Province of northwestern China is currently considered as a potential host rock for HLW repositories.[13] With the purpose to systematically investigate the long-term behavior of the Beishan granite under relevant repository condition, an experimental program focusing on creep tests was designed and conducted. In this study, by employing a 3D acoustic emission monitoring system, a special attention is paid on the temperature and stress effect on cracking process and time-dependent behavior of the Beishan granite. An overview of the main results is provided in this paper.

2. Previous studies on the time-dependent behavior of the Beishan granite

The first deep borehole BS01 in the Beishan area was completed in October of 2000. Up to now, thirteen deep boreholes (600 m) located in three subareas, i.e., Jiujing, Jijicao, and Xinchang subareas, have been drilled. Symmetrical investigations of the geological, hydrogeological environment and mechanical behavior of host rock have been con-

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Table 1
Testing conditions of multi-step creep tests (add L-23-0).

Specimen number	Depth (m)	Confining Pressure (MPa)	Temperature T (°C)	Test plan (MPa)				Failure stress (MPa)	Time to failure (d)	Axial strain at failure (%)
				1st step	2nd step	3rd step	4th step			
L-23-0	497.29–497.40	0	23	30.76	61.52	92.28	128.8	112.3	21.11	0.27
L-23-1	595.71–595.82	1	23	41.68	83.36	125.05	173.19	147.12	21.41	0.30
L-90-1	497.40–497.51	1	90	41.9	83.8	125.7	173.19	145.42	21.42	0.31
L-23-5	598.82–598.93	5	23	48.19	95.9	144.57	200.73	182.05	21.03	0.41
L-90-5	497.68–497.79	5	90	48.63	96.77	145.4	200.73	176.83	21.87	0.39
L-23-10	598.93–599.04	10	23	55.94	112.37	168.32	235.15	224.74	21.75	0.53
L-90-10	497.79–497.90	10	90	56.92	113.65	170.23	235.15	206.63	21.12	0.54
L-23-15	599.04–599.15	15	23	64.41	129.31	193.72	229.34	229.34	164.71	0.58
L-90-15	497.57–497.68	15	90	64.78	130.05	194.83	269.58	213.48	20.19	0.58

ducted.[14–16] With the rock samples taken from BS01 which is classified as porphyritic monzonite granite, a series of mono-step creep tests under different confining pressures and temperatures were firstly performed in HongKong University.[17,18] According to the test data, increasing confining pressure tends to make the specimen more stable, and to increase the time to failure. The effect of temperature from room temperature to 90 °C on creep behavior is observed, but found to be not obvious.[18] In this work, the attention is mainly paid on the time-dependent strength degradation of granite, and the loading stress was relatively too high to allow drawing clear conclusions about the stress effect at different level on the cracking process and rock failure.

The Xinchang subarea, located northeast of Jiujing subarea is currently considered as the most potential subarea for disposal purpose. Indifferent from the rock mass in Jiujng subarea, the rock formation in Xinchang is mainly classified as fine-medium-grained granodiorite. Until now, the time-dependent investigation on the granite in this area is still quite limited.

3. Multi-step creep tests

3.1. Design of the multi-step creep tests

To investigate the temperature and stress effect on the time-dependent behavior of the Beishan granite, a series of multi-step creep tests were conducted at first. The multi-step creep test plan constitutes of nine cases conducted at confining pressures of 0 MPa, 1 MPa, 5 MPa, 10 MPa and 15 MPa and at temperatures 23 ℃ (room temperature) and 90 ℃, respectively. The in situ stress measurement by hydrofracturing method in Beishan showed that the maximum stress varies from about 10–27 MPa in Beishan region from 400 m to 600 m in depth, with an average value of about 15 MPa. Thus, 10 MPa and 15 MPa were chosen to simulate the in situ stress level. In view that the mechanical behavior of the surrounding rock after excavation plays a critical role to the evolution of the excavation damaged zone (EDZ), the time-dependent behavior under relatively low confinements (0 MPa, 1 MPa and 5 MPa) is also of special interest in this work. 90 ℃ is the maximum temperature on the canister surface according the current disposal conceptual design in China. In the experimental study, a series of conventional mechanical compression tests under uniaxial and triaxial compression test was performed as first to get the main mechanical properties of the rock, like the Module Young, nonlinear mechanical behavior and the average peak strength at different stress condition. During the creep test, the applied stress is increased stepwise at a certain percentage of the average peak stress (20%, 40%, 60%, 80%) to study the stress level on the time-dependent behavior, and the loading stress at each step was kept constant for one week.

The granite studied in this work is taken from the borehole BS06 in Xinchang subarea within two depth ranges (480–500 m and 590–603 m). The granite can be classified as fine-medium-grained with a grain density of 2.7 g/cm^3, mainly composed of approximately 52% plagioclase, 17% quartz, 15% alkalifeldspar, 12% biotite, 3% albite, and < 1% myrmekite. According the previous mechanical study,[19] its average uniaxial compressive strength is about 160 MPa, and a brittle-ductile transition is observed with the increase of confining pressure. Note that some slight difference of the mechanical behavior of rock samples taken from different depth ranges is noticed due to the heterogeneity of rock mass. Therefore, the test data of rock specimens at different depth range will be analyzed separately in case of necessary in this study.

Dry specimens with the dimension of Φ50 mm×H100 mm were prepared following the Standard for Test Method of Engineering Rock Mass (GB/T50266-2013).[20] A computer-controlled creep setup is employed in the tests, with the capacities of axial loading in the range of 0–600 kN and confining pressure in the range of 0–30 MPa, and the axial deformation is measured by a variable differential transducer