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Technical Note

Influences of pore pressure on short-term and creep mechanical behavior of red sandstone

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ABSTRACT

Short-term and creep tests for saturated red sandstone under different pore pressures were carried out by a rock servo-controlled triaxial equipment. Based on the experimental results, the influences of confining pressure and pore pressure on short-term mechanical behavior of red sandstone are firstly analyzed. The results show that the peak strength of dry red sandstone increases with the confining pressure, which can be better expressed by the nonlinear Hoek–Brown criterion than the linear Mohr–Coulomb criterion. But with the increase of pore pressure, the peak strength and elastic modulus of saturated red sandstone all decrease step by step. The short-term failure mode of red sandstone is dependent of the confining pressure, but independent of the pore pressure. And then, the influence of pore pressure and axial deviatoric stress on the creep mechanical behavior of saturated red sandstone is analyzed quantitatively. Creep contribution to rock deformation increases with the pore pressure, and the specimens show significant time-dependent effect at higher deviatoric stresses. However, the steady-state creep rate of saturated red sandstone increases nonlinearly but the viscosity coefficient decreases gradually with increasing axial deviatoric stress and pore pressure. An exponential function is suggested to characterize the relationship between the creep parameters (including creep strain, steady-state creep rate and viscosity coefficient) and the axial deviatoric stress, and pore pressure. The calculated curves using the proposed function are compared with the experimental results, which is in a good agreement with the experimental data. In the end, the mechanism that the pore pressure and deviatoric stress affect the creep deformation of saturated red sandstone is discussed in detail. The presented experimental results on short-term and creep mechanical behavior of red sandstone under different pore pressures are very significant for evaluating the long-term stability and safety of deep underground rock mass engineering.

1. Introduction

Time-dependent mechanical behavior (including creep, relaxation, loading rate effect, etc.) of rock material is very important for evaluating the stability and safety of key rock engineering, such as deep underground rock engineering, high slope rock engineering, dam base rock engineering and nuclear waste disposition project (Yang et al., 1999; Xie et al., 2011; Yang and Cheng, 2011; Yang et al., 2011; Yang and Jing, 2013). In the past decades, the short-term deformation parameters (e.g. elastic modulus and Poisson's ratio) of rock were often adopted for the design of rock engineering and numerical analysis of stability. Compared with short-term deformation of rocks, the creep deformation considering time effect was negligible. However, in the design of key rock engineering, the predicted deformation data neglecting time-dependent effect could have a large difference with real field measurements (Maranini and Brignoli, 1999; Weng et al., 2010), which may lead to an incorrect evaluation and even serious disaster (e.g. landslide and large deformation failure). Sandstone is a sedimentary rock that is widely used in all kinds of rock engineering. It is very important to know the short-term and creep mechanical behavior of sandstone in many engineering applications (e.g., the design of high slope and the evaluation of tunnel deformations).

In the past, a lot of investigations have been made regarding the short-term strength, deformation, and AE behaviors of sandstone. Bésuelle et al. (2000) conducted triaxial compression experiments on Vosges sandstone with two slenderness ratios, and observed a strong positive dilatancy at lower confining pressures, which decreased and became negative at higher confining pressures. Furthermore, they also analyzed inside the shear band using X-ray computerized tomography (CT) and scanning electron microscopy (SEM). Baud et al. (2000) investigated water-weakening in the cataclastic flow regime on Berea, Boise, Darley Dale, and Gosford sandstones. They found that the presence of water reduced the strength of the sandstones and altered the failure mode at elevated pressures. Gatelier et al. (2002) presented an extensive experimental study on the mechanical behavior of anisotropic porous sandstone, which analyzed the influence of the structural anisotropy on the progressive development of pre-peak damage. Fortin et al. (2009) investigated shear localization, compaction localization, and cataclastic compaction in Bleurswiller sandstone using 3D AE

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locations. They found that compaction localization and cataclastic compaction generate similar AE signatures to shear localization. Wasantha et al. (2014) investigated the mechanical behavior and energy releasing characteristics of dry and saturated bedded-sandstone by adopting the acoustic emission technique. Yang and Jing (2013) evaluated the strength and deformation behavior of red sandstone under simple and complex loading paths. Peng et al. (2013) analyzed the influence of pore pressure on crack propagation of sandstone by experiment, which indicated that with the increase of pore pressure, crack initiation stress had a tendency to increase, but crack damage stress and peak strength decreased gradually. Shukla et al. (2013) presented the experimental results conducted for characterizing the brittle failure processes induced in a rock due to monocyclic uniaxial compression on loading of two types of sandstone specimens saturated in NaCl.

However, very few test results have been reported regarding creep mechanical behavior of sandstone under triaxial compression, especially under the experimental conditions of pore pressure. Baud and Meredith (1997) performed triaxial creep tests on water-saturated specimens of Darley Dale sandstone to investigate the effect of deviatoric stress on the process of creep deformation. During creep test, the axial strain, AE output and pore volume change were all monitored continuously, which showed that the variations of axial strain and differential pore-fluid volume were more regular when the tests were conducted at stresses closer to the strength of the material. Tsai et al. (2008) presented a systematic experimental data regarding time-dependent deformation of a typically weak sandstone, which obtained details of plastic flow, viscoplastic flow, the plastic dilation threshold, the viscoplastic creep dilation threshold, and the yield surface of rocks under various stress conditions. Heap et al. (2009) studied time-dependent brittle deformation in Darley Dale sandstone and found that the rate of creep deformation during constant stress experiments was heavily dependent on the applied deviatoric stress. Yang and Jiang (2010) investigated the creep mechanical behavior of sandstone from Xiangjiaba Hydropower Project under different confining pressures, which gave a detailed analysis on the tertiary creep mechanical behavior of sandstone.

But in the previous experimental studies for creep mechanical behavior of sandstone, pore pressure is less taken into account in a triaxial creep test. Therefore, in this paper, we have performed a series of short-term and creep experiments on red sandstone under different pore pressures. The emphases of this research are to investigate the effect of pore pressure on short-term strength and deformation of saturated red sandstone, to analyze the influence of pore pressure and axial deviatoric stress on the creep mechanical behavior of saturated red sandstone, and to construct the quantitative relationship between the creep parameters (including creep strain, steady-state creep rate and viscosity coefficient) and the axial deviatoric stress, and pore pressure. In the end, we also discuss the mechanism that the pore pressure and deviatoric stress affect the creep deformation of saturated red sandstone.

2. Tested material and testing equipment

2.1. Tested material

To investigate the short-term and creep mechanical behavior of rock under the action of different confining pressures and pore pressures, the red sandstone material located in Shandong province of China was selected for the experimental study. The mineral components of tested red sandstone material were feldspar, quartz, debris and agglutinate according to optical microscopy and SEM results. The mass content of agglutinate in red sandstone material consisted of gypsum, barite and iron integument. Red sandstone (Figure 1) is a fine- to medium-grained, feldspathic sandstone with a connected porosity of 8.6%.

All triaxial experiments were carried out on cylindrical specimens 50 mm in diameter and 100 mm in length in accordance with the ISRM standard (Fairhurst and Hudson, 1999). The specimens were all cored from the same large rectangular block and in the same orientation. All the experiments were carried out on dry or saturated specimens at room temperature. The average dry density of tested red sandstone was approximately 2390 kg/m^3. Table 1 listed tested red sandstone specimens and conditions in this research. It should be

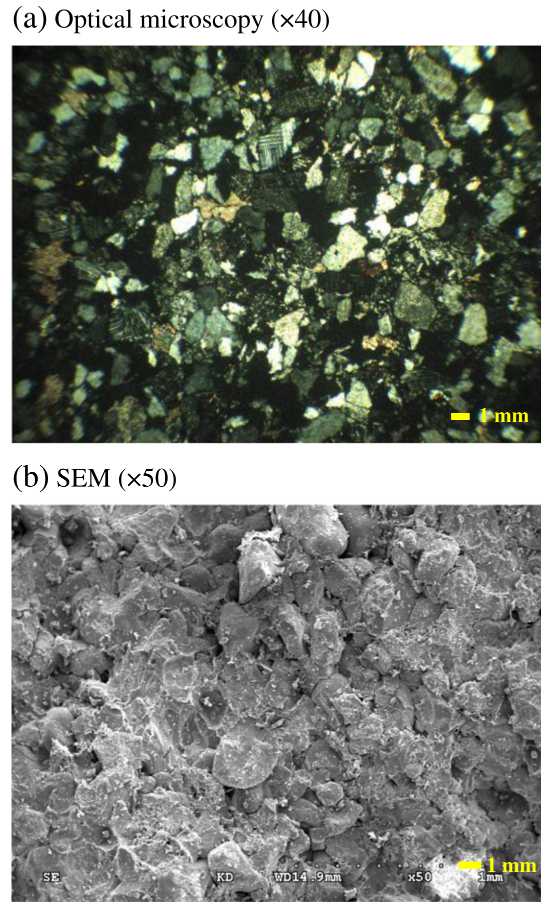

Fig. 1. Optical microscopy and SEM photomicrographs of red sandstone.

Table 1
Tested red sandstone specimens in this research.

Specimen	Diameter/ mm	Length/ mm	Mass/ g	Dry density/ (kg/m^3)	Description	Testing design
RS-b03#	50.3	103.9	490.3	2375	Dry	Short-term loading
RS-b04#	50.2	100.5	474.4	2385	Dry	Short-term loading
RS-b28#	50.2	100.6	493.6	2479	Dry	Short-term loading
RS-b02#	49.4	102.9	483.0	2449	Dry	Short-term loading
RS-b27#	50.2	102.2	490.4	2424	Saturated	Short-term loading
RS-b08#	50.2	103.5	487.0	2377	Saturated	Short-term loading
RS-b06#	50.4	104.5	491.8	2359	Saturated	Short-term loading
RS-b19#	50.2	101.7	484.1	2405	Saturated	Multi-stage creep
RS-b29#	50.2	103.4	486.9	2379	Saturated	Multi-stage creep
RS-b07#	50.2	103.7	485.7	2366	Saturated	Multi-stage creep