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Experimental study on deformation, peak strength and crack damage behavior of hollow sandstone under conventional triaxial compression

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ABSTRACT

Based on a series of triaxial compression experiments using hollow sandstone specimens with various hole diameters ($d = 0, 11, 15$ and 26 mm), the deformation, peak strength and crack damage behavior of hollow sandstone specimens under different confining pressures are investigated. The experimental results show that the Young's modulus of hollow sandstone only depends on the confining pressure and is not affected by hole diameter in the tested range of $d = 0$–26 mm. Two types of methods used to confirm the elastic modulus and Poisson's ratio of rock material are proposed to evaluate the triaxial deformation characteristics of hollow sandstone. The effects of confining pressure and hole diameter on the Poisson's ratio and peak strain of hollow sandstone are analyzed. The peak strength and crack damage parameters of hollow sandstone depend on not only the confining pressure (σ_3) but also the hole diameter. Under uniaxial compression, the peak strength and crack damage threshold (σ_{cd}) of hollow sandstone are independent of hole diameter, whereas the triaxial compressive strength of hollow sandstone decreases linearly with increasing hole diameter. The peak strength and crack damage threshold of hollow sandstone increase with increasing confining pressure, which can be better described by the nonlinear Hoek-Brown criterion than by the linear Mohr-Coulomb criterion. Furthermore, the sensitivity of the crack damage threshold of hollow sandstone to hole diameter is lower than that of peak strength on hole diameter. The concluding remarks can be used to improve the stability and safety of deep underground engineering.

1. Introduction

Sandstone is a typical sedimentary rock that is widely used in all types of rock engineering. Therefore, knowledge of the mechanical behavior of sandstone is very important in geotechnical engineering (e.g., the design of waste repositories) and petroleum geoscience (e.g., the prediction of reservoir deformation and fluid flow). In the past, many experimental investigations have been carried out on the strength and deformation behavior 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. Gatelier et al. (2002) presented an extensive experimental study on the mechanical behavior of anisotropic porous sandstone, and analyzed the influence of the structural anisotropy on the progressive development of pre-peak damage. Yang et al. (2012) performed an experimental study on red sandstone under conventional triaxial compression and reduced confining pressure, and analyzed the influence of confining pressure and loading path on the strength, deformability, failure behavior and acoustic emission locations. Yang and Jing (2013) evaluated the strength and deformation behavior of red sandstone under simple and complex loading paths. Wasantha et al. (2014) investigated the mechanical behavior of dry and saturated Hawkesbury sandstone and analyzed the influences of confining pressure and pore pressure on the peak strength and failure behavior.

During construction, a disturbed or damaged zone may develop around the excavation boundary of a tunnel, cavern, borehole or excavated surface. It is essential to evaluate the stress levels at different stages of the crack evolution of rock and estimate the extent of the disturbed zone.

The crack damage threshold of rock is indicative of the long-term strength (Martin and Chandler, 1994), above which failure of the rock specimen would occur. Xue et al. (2014) investigated the influences of rock type, porosity and grain size on the crack damage threshold of rock. Ghazvinian et al. (2015) analyzed the influence of the existence of fabric-guided micro-fracturing phenomenon on the crack damage threshold in four different types of brittle rocks with different types of fabric. Based on an experimental and theoretical study of crack damage in intact rocks, Cai et al. (2004) generalized the crack damage thresholds of jointed rock masses, and a deviatoric stress criterion was used to describe the crack damage surfaces in the principal stress space. Kim et al. (2015) presented criteria for crack initiation and damage thresholds in granite to assess the evolution of progressive damage, with the AE technique. They subsequently compared the results with those obtained

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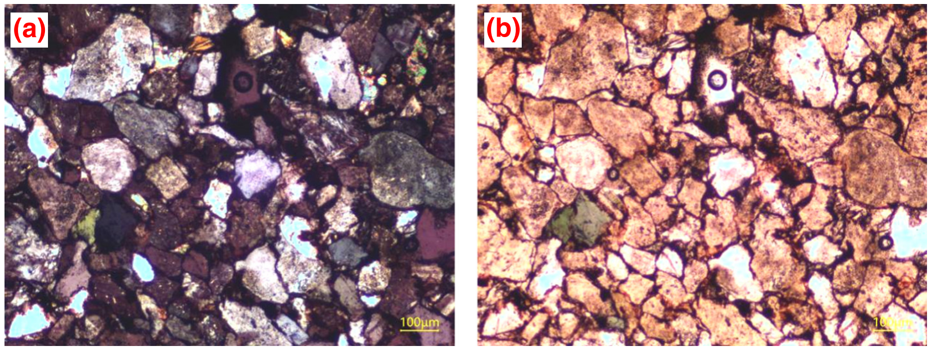

Fig. 1. Thin section images of sandstone used in this research. (a) Crossed polarization photograph of microstructure, and (b) plane polarization photograph of microstructure.

from the stress-strain relationship. Damjanac and Fairhurst (2010) proposed that there is a lower "threshold" strength below which the rock will cease to deform. This threshold is on the order of 40% of the unconfined compressive strength and may be higher for laboratory specimens under unconfined compressive loading. Furthermore, the absolute value of the threshold increases rapidly with confinement, which is of comparable magnitude to the long-term strength of crystalline rock.

However the above experimental studies have mainly focused on conventional solid cylinder specimens. The testing of hollow cylinder specimens in rock engineering is very common and has at least two advantages compared to testing conventional solid cylinder specimens. The first advantage is that tests using hollow cylinders can both evaluate rock behavior and perform physical simulation at reduced scale of rock engineering applications (Alsayed, 2002; Labiouse et al., 2014). The second advantage is that tests using hollow cylinders can better simulate stress conditions around deep well bores in petroleum engineering or the safety of deep excavation damage zones in tunnel engineering (Monfared et al., 2011; Haimson and Kovacich, 2003). Lee et al. (1999) carried out a series of hollow cylindrical triaxial tests to investigate the potential effect of stress path on the mechanical behavior of sandstone. Alsayed (2002) developed a new multiaxial hollow cylinder test cell and demonstrated its versatility by performing uniaxial, biaxial, triaxial and polyaxial compression tests on hollow sandstone specimens. But, in the past, few experimental studies have analyzed the deformation, peak strength and crack damage behavior of hollow sandstone with various hole diameters.

Therefore, in this paper, the results of a series of conventional triaxial compression tests using hollow sandstone with various hole diameters are reported. Based on the experimental results, the influences of confining pressure and hole diameter on the deformation parameters of hollow sandstone are first discussed. Then, the effects of hole diameter and confining pressure on the peak strength parameters of the hollow sandstone are investigated in detail. Finally, the effects of hole diameter and confining pressure on crack damage behavior of the hollow sandstone are analyzed in detail.

2. Hollow sandstone and testing procedure

2.1. Sandstone material and hollow specimen preparation

The material used throughout this study was sandstone collected from Rizhao city in Shandong province, China. The sandstone material (Fig. 1) is a fine- to medium-grained, feldspathic rock material with a connected porosity of 6.88% and a bulk density of 2410 kg/m^3. According to the results of X-ray diffraction (XRD), the minerals in the sandstone material are quartz, K-feldspar, plagioclase, calcite, dolomite, hematite and clay mineral. The detailed composition of this rock is described as follows: 10.1% quartz, 11.7% K-feldspar, 41.6% plagioclase, 10.7% calcite, 13.1% dolomite, 2.4% hematite and 10.4% clay minerals. In this experiment, all intact specimens were cored from the same block of material to an actual diameter of 49.8 mm and approximate length of 100 mm. Based on intact specimens, hollow specimens with hole diameters (d) of 11, 15 and 26 mm (Fig. 2) were machined successfully. The machining method can be described as follows: Internal holes are first drilled in a large rectangular rock block (approximately 600 ∗ 600 ∗ 120 mm) using diamond bits with various outer diameters ($d = 11$, 15 and 26 mm). Then, a larger diamond bit with an internal diameter of 50 mm is used to machine the hollow specimens. All the experiments were performed on dry specimens at room temperature. The average P-wave velocity and S-wave velocity of the tested sandstone are 3813 m/s and 2290 m/s, respectively.

2.2. Testing equipment and procedure

All experiments were performed in a TAW-1000 servo-controlled rock mechanics experimental system (Yang et al., 2015). The maximum loading capacity of the servo-controlled system is 1000 kN, and the maximum confining pressure is 60 MPa. During experimentation, the axial deformation was measured with an axial linear variable differential transducer (LVDT) with a range of 8 mm. The radial deformation was measured using an LVDT wrapped tightly around the specimen,

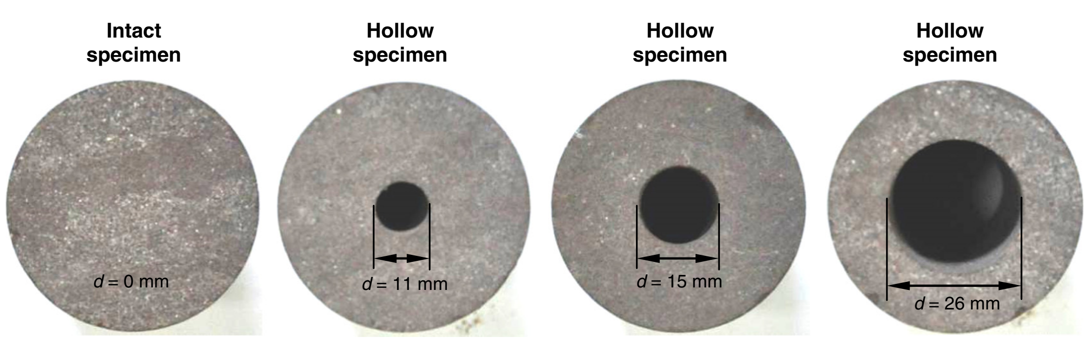

Fig. 2. Intact specimen and hollow specimen in the present study.