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Experimental investigation on the effect of wetting-drying cycles on mixed mode fracture toughness of sandstone

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A R T I C L E I N F O

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1. Introduction

Rock deformation and failure usually involves water in practical engineering scenarios like tunneling, mining and excavation. The rock mass is often subjected to cyclic wetting and drying due to factors such as variable levels of rainfall and evaporation, and changes of ground water and reservoir water levels. The periodic water-rock interaction significantly affects the physical and mechanical properties of the rock mass and accelerates rock weathering.[1] In general, these weathering processes involve a combination of two overarching categories, physical and chemical weathering. Many geological disasters such as landslides, debris flows, ground subsidence and collapse have occurred in the past few decades, which are closely related with the water-rock interaction. The water-rock interaction has been recognized as an important factor which affects the safety and stability of geotechnical engineering structures and it is increasingly becoming an important focus of attention.[2,3]

In recent years, a series of experimental investigations on the effect of cyclic wetting and drying on the physical and mechanical properties of rock materials have been carried out by researchers. The results indicated that the physical and mechanics properties (such as specific gravity, apparent porosity, bulk density, P-wave velocity, elastic modulus, uniaxial compressive strength, shear strength, etc.) have different degrees of deterioration after cyclic wetting and drying.[4–14] Hale and Shakoor[15], Özbek[16] and Khanlari and Abdilor[17] investigated the effects of cyclic wetting and drying, and freezing and thawing on particular physical and mechanical properties of selected rocks. Yuan and Ma[1] conducted a number of uniaxial impact compressive tests for sandstone after cyclic wetting and drying by using the split Hopkinson pressure bar system, and they pointed out that cyclic wetting and drying has a large deterioration effect on the dynamic energy absorption of sandstone. A damage constitutive model for rock considering the drying-wetting effect was proposed by Li and Zhang[18], that can correctly reflect the change rules of uniaxial compressive stress-strain for sandstone under cyclic drying and wetting conditions. The influence of water content on uniaxial compressive strength, elastic modulus and tensile strength of rock materials has been investigated by Erguler and Ulusay[19] and Török and Vásárhelyi.[20] It is widely knowledged that the water content is one of the most important factors lowering the strength of rocks, and rocks with higher clay content slake more rapidly and extensively under natural climatic conditions than those with lower clay content.[21] Moreover, the slake durability of rock is strongly related to the atmospheric conditions in the wetting and drying cycle.[22]

Nara et al. [23,24] investigated the effects of relative humidity and temperature on subcritical crack growth in igneous rock and sandstone by using the Double Torsion technique. They concluded that subcritical crack growth is greatly affected by the relative humidity, which needs to be controlled to avoid time-dependent weakening and in extending the life of structures in a rock mass. Furthermore, the effect of the relative humidity on the mode I fracture toughness of rocks at constant temperature was also investigated by Nara et al.[25], and the results indicated that the fracture toughness of rocks decreased in the presence of high relative humidity. In addition, it was much more pronounced when the rocks included expansive clays such as smectite. Tang et al.[26] and Deng et al.[27,28] conducted some experimental investigations on the

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mode I fracture toughness of rock materials under water-rock interaction using three pointed bending specimens. Recently, we investigated the influence of cyclic wetting and drying on the pure mode I and pure mode II fracture toughness of sandstone. It was found that the crack propagation radius of sandstone decreases gradually with increase in the wetting-drying cycle,[2] in addition, the degradation degree of pure mode II fracture toughness is always larger than that of pure mode I.[3] However, up to now, few investigations on how wetting-drying cycles affect the mixed mode fracture toughness of rock materials have been reported.

On the other hand, because of the arbitrary orientation of micro-cracks in natural rock masses and the complex loading conditions, rock failure is mainly due to the influence of both the opening (mode I) and sliding (mode II) of the deformation, and most brittle rock fractures occur under mixed mode loading conditions.[29] Therefore, it is necessary to investigate the mixed mode fracture behavior of rock materials using suitable theoretical and experimental methods. A number of experimental methods and test configurations have been adopted by researchers to determine the fracture toughness of brittle materials like rocks in the past few decades. Some well-known test configurations are the single-edge crack specimen subjected to asymmetric four point bending loading,[30] the angled internal cracked plate under biaxial far field loading,[31] the edge cracked semi-circular specimen subjected to three point bending[29] and the centrally cracked Brazilian disk (CCBD), diametrically subjected to compressive loads.[2,3,32–35] Among these specimens, the centrally cracked Brazilian disk specimen has been recognized as a favoured test specimen for conducting fracture toughness experiments. The major advantages of this specimen are: convenience of test specimen preparation, simple geometry and easy test set up with commonly available loading fixtures, introducing full mode combinations ranging from pure mode I to pure mode II by changing the loading angle and the existence of closed-form solutions for the stress intensity factors.[34,35] Therefore, this specimen has been frequently used by researchers for determining the mixed mode fracture toughness of brittle materials such as rocks.

In this research, we have conducted a series of fracture tests on sandstone with centrally cracked Brazilian disk specimens to investigate the effect of wetting-drying cycles on mixed mode (I-II) fracture toughness. Moreover, the degradation mechanism of wetting-drying cycles is also discussed in this paper. Finally, the experimental results are compared with the theoretical values calculated by the generalized maximum tangential stress (GMTS) criterion in order to provide a theoretical basis for stability analysis in geotechnical engineering structures under complex conditions.

2. Experimental methods

2.1. Stress intensity factors for the centrally cracked Brazilian disk

A schematic diagram of the centrally cracked Brazilian disk specimen diametrically subjected to a pair of concentrated forces P is shown in Fig. 1. The thickness of the disk is represented by B and the radius as R. The crack length is $2a$, and the loading angle is β, which is the angle between the crack line and the loading direction. Dong et al.[35] obtained closed-form solutions for the stress intensity factors for the centrally cracked Brazilian disk under mixed mode loading conditions by using the weight function method.

$$K_I = \sigma\sqrt{\pi a}\left[f_{11} + 2\sum_{i=1}^{n} A_{1i} f_{1i}\,\alpha^{2(i-1)}\right] \tag{1}$$

$$K_{II} = 2\sigma\sqrt{\pi a}\sum_{i=1}^{n} A_{2i} f_{2i}\,\alpha^{2(i-1)} \tag{2}$$

The normalized stress intensity factors F_{I} and F_{II} can be written in the following forms:

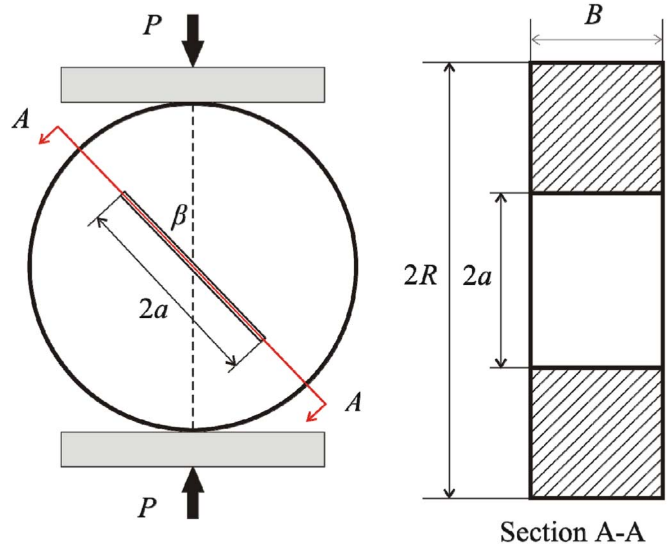

Fig. 1. Schematic diagram of the centrally cracked Brazilian disk specimen under mixed mode loading.

$$F_I = \frac{K_I}{\sigma\sqrt{\pi a}} = f_{11} + 2\sum_{i=1}^{n} A_{1i} f_{1i}\,\alpha^{2(i-1)} \tag{3}$$

$$F_{II} = \frac{K_{II}}{\sigma\sqrt{\pi a}} = 2\sum_{i=1}^{n} A_{2i} f_{2i}\,\alpha^{2(i-1)} \tag{4}$$

where $\alpha=a/R$ and $\sigma=P/(\pi BR)$, and α is defined as the relative crack length. The expressions for the coefficients f_{11}, A_{1i}, f_{1i}, A_{2i} and f_{2i} are given by Dong et al. [35] When n=100, the normalized stress intensity factors are very accurate for the centrally cracked Brazilian disk with a relative crack length not more than 0.9. Therefore, the value of 100 is used for all the calculations in this paper.[2]

2.2. Specimens preparation and testing procedure

The sandstone for this experiment was produced in Ziyang City, Sichuan Province, China. The dry density of this selected sandstone was 2.10 g/cm^3, moisture content was 1.2%, water absorption was 7.5%, and the tensile strength was 1.18 MPa. The mineralogical composition of the sandstone was determined by X-ray diffraction (XRD) analysis, indicating that it was mainly composed of quartz, albite, chlorite and serpentine.[2] The centrally cracked Brazilian disk specimens were used for mixed mode fracture toughness testing. Specimen processing included the following steps. Initially, the sandstone cylinders of size 74.5 mm in diameter were obtained from the rock mass by drilling cores, then the cylinders were cut into pieces of thickness 25 mm. Later, the disk specimens were fixed in a special fixture for processing a herringbone groove crack by coplanar milling with a cutter disk of thickness 0.8 mm. On this basis, the herringbone part of both sides were sawn by using a diamond saw wire with a diameter of 0.5 mm, extending to the root of the groove. Finally, the centrally cracked Brazilian disk specimens with nominal relative crack length of 0.52 were obtained. This specimen processing procedure was illustrated in Fig. 2.

According to the definition of pure mode II loading, a pure mode II crack can be determined from the conditions in which F_{I}=0 and $F_{\mathrm{II}}\neq$0.[35] The critical loading angle for the pure mode II was 22.41° as obtained from Eq. (3) and the geometric size of the specimens. Therefore, various combinations of mode I and mode II can be easily achieved by changing the loading angle β from 0° to 22.41°. In this research, only two cases with loading angles of 10° and 15° were taken into account for the mixed mode fracture tests.

Wetting-drying cycles were performed by submerging the speci-