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Effects of water content on fracture and mechanical behavior of sandstone with a low clay mineral content

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ABSTRACT

This study investigated the effect of water content on quasi-static fracture behavior of sandstone. Notched semi-circular bending (NSCB) tests were conducted on a total number of 20 sandstone specimens with different water contents (0, 1.0, 2.0 and 3.5%) to determine their fracture toughness. During the NSCB tests, the cracking process and acoustic emission (AE) signals were recorded continuously with the aid of a charged couple discharge (CCD) camera and an AE system, and the crack propagation velocity was also measured accurately via a crack propagation gauge (CPG). Test results demonstrated that both the fracture toughness and crack propagation velocity observably decreased with the increase of water content, the variation trend of which could be described by exponential equations. The cumulative AE counts of wet specimens in the NSCB tests were much less than those of dry ones, which indicated that the sandstone specimens underwent more ductile failure and released less elastic energy due to water-softening effects.

1. Introduction

It is well known that water could significantly degrade strength and stiffness of rock materials, as well as increase their deformability [1], which would be related to many rock engineering disasters, e.g., landslides [2], karst collapse [3] and deformation of dam foundation [4]. In recent years, water effects on mechanical properties of rock materials have become a research focus due to the important practical value.

A substantial effort of research about mechanical properties of rocks affected by water has been mainly concentrated on compressive strength [5–10], tensile strength [7,9,11–15] and tri-axial tests [16–18]. Although it is hard to quantitatively predict the variation in strength for certain rock types, there is a universally acceptable viewpoint that rock materials would suffer a strength loss to some extent in the presence of water. However, compared to the mechanical properties mentioned above, the fracture behavior of rocks under water conditions has been less investigated. In fact, the mode-I fracture toughness (K_{IC}) is one of the most crucial mechanical parameters for rock fragmentation which reflects the ability of rock to resist the crack initiation and propagation. Therefore, the investigation regarding the water effects on the fracture behavior is of tremendous significance to rock engineering applications such as mining, blasting, tunneling and underground excavation.

There are only a few attempts in literatures in which the effect of water on fracture toughness of rock-like materials was considered [19–27]. For example, Peck and Gordon [19] measured the fracture energy of quartzite in air and water with the wedged-loaded double cantilever beam (DCB) method and reported that the fracture energy of rock in water was15% lower than that

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Nomenclature

AE	acoustic emission
CCD	charged couple discharge
CPG	crack propagation gauge
K_{IC}	mode I fracture toughness
DCB	double cantilever bending
SENB	single-edge notched beam
SENB(T)	SENB subjected to three-point bending
SENB(F)	SENB subjected to four-point bending
SENRB(T)	single-edge notched round bar subjected to three-point bending
CCNBD	cracked chevron notched Brazilian disc
DT	double torsion
CENRB(T)	chevron-edge notched round bar subjected to three-point bending
NSCB	notched semi-circular bending
CB	chevron bend
SR	short rod
SIF	stress intensity factor.
G_{I}	fracture energy
K_{IC}	Mode-I fracture toughness
K_{IQ}	apparent fracture toughness
K_{IIC}	Mode-II fracture toughness
K_{eff}	mixed-mode fracture toughness.
V_{sc}	subcritical crack growth velocity
SEM	scanning electron microscope
EDX	Dispersive X-ray spectrometer
ISRM	International Society for Rock Mechanics
DIC	digital image correlation
ROI	region of interest
ROC	region of camera
FPZ	fracture process zone
w	water content of specimen (%)
m_w	wet mass of specimen (g)
m_d	dry mass of specimen (g)
$P(t)$	applied loading on the specimen (N)
l_n	notch length
R	radius of specimen (mm)
B	thickness of specimen (mm)
Y'	non-dimensional stress intensity factor
S	distance between the two supporting pins
R^2	correlation coefficients

measured in air. But only dry and saturated states of specimen were considered in this test. Haberfield and Johnston [21] and Lim [22] further studied the effect of water content on fracture toughness of a synthetic rock and found that fracture toughness decreased with the increase of water content. Nara et al. [25] and Hao et al. [26] also conducted a series of double torsion (DT) tests on rocks to investigate the influence of water on fracture toughness and subcritical crack growth velocity. Guha Roy et al. [27]experimentally investigated the fracture properties of water saturated sedimentary rocks and reported that all the fracture properties decreased with the increasing degree of saturation. More detailed information concerning the fracture behavior of rock-like materials under moisture conditions is summarized in Table 1. However, no systematic experimental research has been performed to study fracture behavior of rocks with various water contents ranging from dry to saturated state, and the acoustic emission (AE) characteristics in fracture tests and the crack propagation velocity affected by water are not investigated yet.

In this study, in order to gain a comprehensive understanding of the effect of water content on the quasi-static fracture behavior of sandstone, a series of fracture tests were carried out on sandstone specimens at different levels of water content using the notched semi-circular bending (NSCB) method to determine the fracture toughness. Furthermore, the AE characteristics of rock with different water contents were recorded in the NSCB tests, and the relationship between water content and crack propagation velocity was also obtained.

2. Experimental program

2.1. Rock description

The rock material used in this study was a sandstone collected from northwest of Kunming, Yunnan province of China. It is fine-grained and considered to be isotropic and homogeneous. Fig. 1 shows the microscopic image of a thin section obtained by a scanning electron microscope (SEM Quanta 250) at a magnification ratio of 1000. It can be seen that the granules of the sandstone are dense and defects are hardly visible except few micro-pores.

The mineral composition of this sandstone was measured using an energy dispersive X-ray spectrometer (EDX MLA 250), and the results of EDX analysis indicates that this sandstone is primarily made up of quartz (42.74%), omphacite (16.85%), calcite (13.9%), hematite (11.19%), feldspar (9.08%) and clay minerals (4.89%) which are mostly smectite with little illite and kaolinite[28]. Some essential physical and mechanical properties were also determined, as listed in Table 2.

2.2. Testing method and specimen preparation

To determine the quasi-static Mode I fracture toughness of rock materials, the International Society for Rock Mechanics (ISRM) has proposed and suggested four standardized procedures and test specimens: chevron bend (CB) and short rod (SR) methods, cracked chevron notched Brazilian disc (CCNBD) method [29–31] and notched semi-circular bending (NSCB) method [32,33]. Many other non-standard fracture testing methods have been widely used, e.g., double torsion (DT) method [25,26], cracked chevron notched semi-circular bending (CCNSCB) [34,35], single-edged notched beam subjected to three (SENB(T)) [20–22] or four (SENB (F)) [23] points bending methods. Among them, the NSCB method has been widely adopted in fracture tests because of its inherent favorable attributes, such as simple geometry, minimal machining requirements for specimen preparation and convenience in testing