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Technical Note

Morphological analysis of sheared rock with water–rock interaction effect

Yu Chen [a,b,*], Ping Cao [a], Dawei Mao [c], Chengzhi Pu [a], Xiang Fan [a]

[a] School of Resources and Safety Engineering, Central South University, Changsha 410083, China
[b] Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, Trondheim N-7491, Norway
[c] HydroChina Zhongnan Engineering Corporation, Changsha 410014, China

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1. Introduction

In a generalized way, water–rock interaction processes can be described as a reaction between an aqueous fluid and a rock in its broadest sense. For engineering rock mechanics, water–rock interaction of rock masses is of increasing interest to the scientific community. One of the most challenging and remaining tasks is accurate characterization of rock surfaces. The surface properties with water–rock interaction have a major influence on the hydro-mechanical behavior of the rock masses and rock joints. Therefore, rock surface morphological description and evaluation with high-resolution are necessary for critical characterization of rock masses and rock joints.

Rock mechanics researchers have tried to carry out a number of laboratory rock shear tests. Patton [1] demonstrated the shear strength by means of an experiment in which he carried out shear tests on 'saw-tooth' specimens. Barton and Choubey [2–4] studied the behavior of natural rock joints and proposed the joint roughness coefficient (JRC) that can reflect the reality of shear strength with increasing normal stress. Bandis et al. [5] described laboratory investigations of the deformation characteristics of rock joints under normal and shear loadings. It was shown that behavior in the pre-peak range is invariably non-linear depending on the joint type, and can be adequately described by easily measured parameters and hyperbolic functions. A model to determine the effect of boundary conditions on the shear behavior of a dilatant rock joint was proposed by Saeb and Amadei [6]. It provided a tangent formulation for the deformability of a rock joint that fully accounts for the coupling between joint normal and shear responses due to dilatancy. Jing et al. [7] investigated experimentally the anisotropy and stress-dependency of the strength and deformability for rock joints through shear tests with concrete replicas of natural rock joints. Li et al. [8] developed a constitutive model that described the relationship between the macro-deformation of rock and the micro-fracture within rock. Gentier et al. [9] performed a series of shear tests on identical copies (replicas) of a natural granite fracture and developed a method to use image processing techniques to identify and quantify damage that occurred during shearing.

In addition to the above empirical studies, many theoretical studies about water–rock interaction have been carried out to examine the mechanical shear behavior of rock. Witherspoon et al. [10] demonstrated the validity of the cubic law for deformable fractures, and the studies on the hydraulic properties of fractures subjected to normal loading were performed by Raven and Gale [11]. Ahola et al. [12] investigated two different laboratory experiments and it was determined that additional tests and improvements to the experimental apparatus were necessary during shear and production of gouge within the joint. A new laboratory technique for coupled shear-flow tests of rock joints was developed by Esaki et al. [13] and it was used to investigate the coupled effect of joint shear deformation and dilatancy. Olsson and Barton [14] presented some experimental results about hydromechanical shearing tests and suggested an improved model for rock joints.

Kulatilake et al. [15] mentioned the necessity to know the effect of parameter values, for 2D profiles, and calculated the accurate parameters by fractal parameters. Brown and Scholz [16] pointed out that the degree of correlation between the contacting surfaces was important to quantify besides the scaling of topography. Lanaro et al. [17,18], Fardin et al. [19–21] and Xia et al. [22] utilized a three-dimensional laser-scanning machine in digitizing morphology of rock

* Corresponding author at: School of Resources and Safety Engineering, Central South University, Changsha 410083, China.
E-mail addresses: joyidol1013@hotmail.com, joyidol@163.com (Y. Chen).

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joint surfaces. This method greatly increases the density of the collected data, the accuracy of the measurements and provides repeatability of results. Recently, Olsson and Brown [23] compared the effects of normal stress and shear offset on fluid flow rates and measured the surface roughness by contact constrainer. Zimmerman et al. [24] conducted high-resolution Navier–Stokes simulations and laboratory measurements of fluid flow in a natural sandstone fracture by using a Talysurf profilometer device. Chen et al. [25] investigated five kinds of saturated rock by using high-resolution 3D morphology measurement and quantitatively comparing 12 different parameters.

Since the majority of rock engineering structures are constructed in rock masses, it is obvious that there is an urgent need to analyze the relationship between rock and water–rock interaction. Parameters such as hydraulic conductivity, frictional resistance and resistance to shearing along discontinuities are the key points of water–rock interaction. However, they are closely correlated with morphology characteristics. Although previous studies have demonstrated aspects regarding rock joint surface roughness, there are not many detailed studies have been proposed to analyze the effect of water–rock interaction of sheared rock. This paper describes the results of the uniaxial compressive shear tests of lherzolite, peridotite, dolomite marble, migmatite and amphibolite specimens, found in China, with the contrast of water–rock interaction. To elucidate the basic morphology characteristics and distribution, the micro-morphology of the fracture surfaces was measured by a 3D laser instrument (Talysurf CLI 2000) with high-resolution (0.5 μm). Twenty different parameters of height feature, texture feature, fractal geometry and frequency spectrum, including some functional parameters utilized from automotive and metal industries for the first time, were proposed innovatively for overall interpretation and analysis.

2. Shear tests compared with water–rock interaction

2.1. Rock samples and solution

Five kinds of rock samples with different petrographic, physical and mechanical properties were collected from Jinchuan no. 2 mine area. Jinchuan mine area is the largest production source of nickel and cobalt in China. Peridotite is a type of coarse-grained igneous rock and consists mostly of olivine and pyroxene. Lherzolite is a type of coarse-grained igneous rock consists mostly of olivine. Marble is a non-foliated metamorphic rock composed of calcite or dolomite. Amphibolite is a metamorphic rock consisting mainly of amphibole, especially the species hornblende and actinolite. Migmatite is a rock that is a mixture of metamorphic rock and igneous rock. The complex environment with water has become one of the most important problems to be solved.

Before the experiment, rocks were cut and polished into cubes (sized 50 mm × 50 mm × 50 mm) with a cutting machine. The solution for the water–rock experiments was obtained from the depth portion of Jinchuan no.2 mine area, where pH value is 7.1. The ion minerals in solution are Ni, Cu, Zn, Cr and $SO_4{}^{2-}$. The mechanical parameters of the rock samples are shown in Table 1. Before the uniaxial compressive shear tests, half of the samples were dried under 30° for 30 days, and the others were immersed in the same PVC containers filled with solution (pH=7.1) for 30 days. In order to obtain the actual engineering results, the sealing measurement was not carried out because of the interaction between the rock and the natural medium. As the solution for the experiments was obtained from the deep mine, it contains some minerals. Over 30 days of immersion, the residual solution of samples was fully absorbed with pieces of test paper. The immersion method used here is different from the ISRM suggested method (e.g. vacuum immersion). In this study, we defined the rock specimens with open-type immersion as 'saturated specimens'. The saturated specimens were tested to contrast with dry specimens.

Table 1
Parameters of rock specimens.

Set	Lithology	State	Quantity	Sample size (mm × mm × mm)
A	Lherzolite	Dry	3	50 × 50 × 50
B		Saturated	3	50 × 50 × 50
C	Peridotite	Dry	3	50 × 50 × 50
D		Saturated	3	50 × 50 × 50
E	Dolomite Marble	Dry	3	50 × 50 × 50
F		Saturated	3	50 × 50 × 50
G	Migmatite	Dry	3	50 × 50 × 50
H		Saturated	3	50 × 50 × 50
I	Amphibolite	Dry	3	50 × 50 × 50
J		Saturated	3	50 × 50 × 50

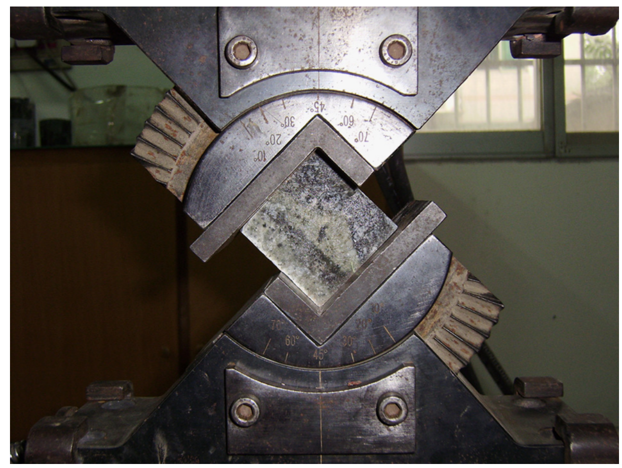

Fig. 1. The spherical seats used for shearing which can be rotated at different angles.

2.2. Testing device and procedure

A special shear testing device (SANS SHT4000 as shown in Fig. 1) for uniaxial compressive shear test was used in this experiment. The rock sample was placed inside the sample holders which were installed between two spherical seats. The spherical seats can be rotated to obtain different angles of shearing (θ). The device was installed in a servo-controlled testing machine. The load applied to the shearing device with a constant displacement rate of 0.005 mm/s was measured by a load cell which was attached to the upper cross-head of the testing machine. Uniaxial compressive shear tests were conducted at three different angles of shearing: 30°, 45° and 60°. Such an arrangement allowed the samples to be investigated under different normal forces with water–rock interaction.

The displacements along normal and tangential directions of the joint were measured by the displacement transducers. A microcomputer was used for data acquisition, reduction and processing. The normal force F_n and tangential force F_t acting on the joint plane are calculated from the relations:

$$F_n = P \cos \theta \quad (1)$$

$$F_t = P \sin \theta \quad (2)$$

where P is the vertical load and θ is the shear orientation angle of the joint plane relative to the horizontal direction. By changing the shear angle, different ratios of tangential to normal force can be