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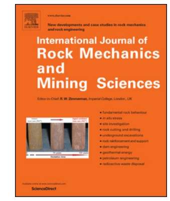

Characteristics of shear-induced asperity degradation of rock fractures and implications for solute retardation

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ABSTRACT

Direct shear tests on a series of fractured Beishan granite samples were performed under different normal stresses, to investigate the characteristics of asperity degradation during shear and to quantify their effects on solute retardation in fractures. A three-dimensional laser scanner and a laser diffraction particle size analyzer were used to examine the shear-induced asperity volume loss and the size distribution of sheared-off fragments. The results identified two main modes of asperity degradation during shear, i.e., instantaneous failure of asperities occurring at the peak shear stress, and crushing of the generated fragments with further shear displacement. Based on the volume of asperity degradation, a new joint damage coefficient was proposed. The size of the sheared-off fragments under different normal stresses was found to follow a Weibull distribution. Combining the proposed joint damage coefficient and the Weibull size distribution of the sheared-off fragments can approximately predict the potential effects of sheared-off fragments on solute retardation coefficient in rock fractures. The results showed that the shear-induced asperity degradation significantly increases the values of the solute retardation coefficient, by offering more sorption surfaces in fracture voids.

1. Introduction

Rock fractures represent geologic planes of relative weakness, and connected fractures provide dominating pathways for groundwater flow and solute transport in fractured aquifers. Therefore, the coupled mechanical-flow-transport processes in fractured rock masses have been the focus of a significant amount of research due to the increasing demands for design, construction, operation and performance/safety assessment of deep underground projects, e.g. radioactive waste repositories, enhanced geothermal systems, CO_2 sequestration facilities and unconventional resource development.

The shear behavior of rock fractures has been extensively studied in the past five decades, in terms of geometry alteration, peak and residual shear strength and the changing ability to transfer fluids and solutes.[1–9] It has been widely recognized that a shear process involves the degradation of fracture asperities and micro-cracking in fracture walls.[5,10–16] The previous laboratory-scale tests focused on the asperity degradation of artificial fractures with either regular (sawtooth) or irregular surfaces, showing that asperity degradation is mainly controlled by the applied normal stress, fracture surface roughness and the strength properties of fracture walls. The main failure modes of asperities during shear include abrasion, adhesion, crushing (of sheared-off fragments) and micro-cracking.[17] Abrasion occurs when contacting asperities, on the two opposite fracture surfaces, plough through each other to produce gouges of relatively large sizes. Adhesion wear represents the generation of small gouges due to gradual breakage of asperities in intimate contacts. The pre-existing or previously-generated gouge material could be further crushed (or comminuted) into a number of smaller fragments with increasing shear displacement, which may significantly change the size distribution of gouge material in fracture voids. The stress concentration at the contact area of asperities can induce micro-crack initiation and propagation into fracture walls in either tensile or shear modes.

Numerical methods have also been used to simulate the asperity damage during shear. Karami and Stead[18] modeled the processes of fracture surface damage during shear using a hybrid FEM/DEM code, showing that fracture surface damage is composed of both surface wear and asperity breakage. Park and Song,[19] Zhao et al.,[17] Asadi et al.[20] and Bahaaddini et al.[16] used the particle mechanics method to simulate the shear behavior of rock fractures, including various failure modes of asperities. Belem et al.[21] proposed two parameters to quantify the wear of fracture walls: the joint interface surface wear coefficient and the

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degree of joint interface surface wear, and confirmed that the sheared surface wear strongly depends on both geometric texture (morphology and asperities interlocking) and material properties (natural rock or mortar). Guo and Qi[22] performed a series of numerical tests to study the progressive failure of rock samples with varying undulated fractures, and found four failure modes: slipping plastic failure, slipping-shearing brittle failure, shearing brittle failure and shearing plastic failure.

It has been quite understood that fracture surface damage can significantly affect the mechanical and hydraulic properties of fractures, e.g., shear strength,[23–25] dilation[26,27] and effective hydraulic aperture (therefore fluid conductivity).[28–30] Using the particle based discrete element model, Zhao et al.[17] showed that fracture surface damage may also influence the solute transport in fractures by producing wear debris (gouges) and creating micro-cracks in the damaged asperities, to adsorb solutes, and then retard the solute migration as a consequence. However, it still remains many uncertainties in the mechanisms by which surface asperities deform and degrade during shear and the possible effects of this degradation on the fluid flow and solute transport in rock fractures. In particular, it remains poorly understood about the size distribution of gouges produced during shear and the influence of gouges on the fracture hydraulic aperture and the potential surface area for solute adsorption.

The main objective of this study is to systematically and quantitatively investigate the surface asperity degradation and the size distribution of the produced fragments during shear, by carrying out direct shear tests on granite fracture samples under different normal stresses. The shear-induced changes in both fracture surface area and the size distribution of sheared-off fragments are carefully scrutinized, and two theoretical models describing shear-induced asperity damage and size distribution of sheared-off fragments are proposed, respectively. The possible effect of asperity damage on the solute retardation coefficient for a single fracture is also discussed.

2. Methods

2.1. Sample preparation

The fracture samples were prepared from the granite collected in the Beishan area, Gansu Province, China, which is a preferred candidate area for China's high-level radioactive waste repository.[31] A random 300-point modal analysis of three thin-sections showed that the Beishan granite is composed of 30% quartz, 35% plagioclase, 25% alkali feldspar, 6% biotite and 4% muscovite in volumetric fraction. The grains range between 0.1 mm and 0.2 mm in size.

To explore the degradation process of asperities under different normal stresses, direct shear testing of fracture samples with identical surface roughness should be performed. It is, however, extremely difficult to obtain samples including natural rock fractures with the same (at least, similar) surface morphology. Due to this, a practical method of sample preparation was used. Similar to the Brazilian tensile testing, one cubic granite block with a side length of 50 mm was axially split, which produced an artificial fracture by jointing together the two rectangular halves of the cubic granite sample (Fig. 1). The artificially-created rough fractures may behave differently from those with natural rough surfaces, but they were thought to be a first suitable step towards a preliminary understanding of the effect of normal stress on the degradation characteristics of asperities. A number of quantitative parameters have been defined to describe the fracture surface roughness, e.g., Joint Roughness Coefficient (JRC), Z_2, and fractal dimension, which can be determined by visual inspection, the statistical method, or the fractal geometry method. The relationships between these surface roughness parameters have also been extensively studied.[29,32–35] The dimensionless parameter Z_2 is one of the most widely used statistical parameter in surface roughness analysis, and is correlated well with JRC. We therefore used Z_2 to describe the fracture surface roughness in this study.

$$Z_2 = \frac{1}{n}\sum_{n}\left[\frac{1}{L}\sum\frac{(z_{i-1}-z_i)^2}{x_{i-1}-x_i}\right]^{1/2} \tag{1}$$

where n is the number of surface profiles; L is the profile length; x_i is the coordinate of the surface profile parallel to the shear direction; z_i is the height of joint surface profile. The average Z_2 of each fracture surface was calculated from 49 surface profiles in a spacing of 1 mm along the direction parallel to the shear direction, i.e., $n = 49$. In total, 6 fracture samples with similar surface roughness (average Z_2 of both fracture sides, 0.34 ± 0.02) were obtained from a representative and massive intact Beishan granite block. The joint matching coefficients of these artificially-created rough fractures are close to 1.0, representing a perfectly matched state.[36]

2.2. Direct shear test

The experiment was conducted using a direct shear apparatus (RLJW-2000).[37] The apparatus consists of two orthogonally arranged pistons which are supported by steel posts and beams with a sufficiently high stiffness (> 5 GN/m), and the pistons are servo-controlled to separately serve the prescribed loading and displacement rates. The lower block of the sample was fixed on the steel basement, and the upper block was in contact by the horizontal piston. The prescribed normal force was first applied perpendicular to the fracture plane by moving up the vertical piston, and then the shear force was applied parallel to the fracture plane with the horizontal piston. To reduce the tangential resistance induced by the top surface of the fracture sample in contact with the vertical piston, a roller plate was placed between the vertical piston and the fracture sample. Normal and shear loads were measured through load cells (DOLI, Germany) with capacities of 180 and 120 kN, respectively. The accuracy of the applied load was ± 1% of the full scale. The horizontal and vertical displacements were monitored with two stroke linear displacement transducers (TE Connectivity) of ± 0.1% precision in the scale of 15 mm, one being attached to the horizontal piston and the other to the vertical piston.

The shear loading was invoked by applying a constant velocity of the horizontal piston at 0.5 mm/min. Three constant normal stresses of 1, 5 and 10 MPa were applied on the fracture samples, respectively. This stress range can represent the vertical in-situ stress level at depths varying roughly from 40 to 400 m, which encompasses a range of interests in rock engineering practices at shallow (e.g., rock slopes) or deep depths (e.g., high-level radioactive waste repositories). Two fracture samples were tested under each normal stress level. Direct shear testing was conducted in accordance with the newly revised ISRM suggested method for laboratory determination of the shear strength of rock fractures.[38]

2.3. Asperity damage observation

A laser scanner (OKIO-5M, TENYOUN) was used to measure the three-dimensional surface topography of the fracture samples before and after shear, respectively. Reference points were applied to each lateral surface of fracture samples, and a couple of measurements from different directions were conducted. Based on the reference points, all the measurements were automatically transformed into a common coordinate system, and then an ASCII point cloud of fracture samples could be obtained by minimizing the deviations between overlapping measurements. In order to examine the shear-induced damage fracture surfaces, we transformed the obtained topographies of fracture samples before and after shear to the same coordinate system by liner transformation of coordinates, and then we aligned the obtained topographies of fracture samples before and after shear using the *Best Fit Alignment* in *Geomagic Qualify* (3D Systems) and calculated the changes in asperity heights on fracture surfaces. The central area of $40 \times 40\ \mathrm{mm}^2$ from fracture surfaces was extracted for analysis and discussion to avoid boundary effects. The achieved resolution was 5 μm.