International Journal of Rock Mechanics & Mining Sciences 88 (2016) 105–114

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Effect of hydraulic hysteresis and degree of saturation of infill materials on the behavior of an infilled rock fracture

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ARTICLE INFO

Article history:
Received 14 July 2015
Received in revised form
1 April 2016
Accepted 6 July 2016

Keywords:
Infilled rock fracture
Unsaturated state
Shear strength
Soil water characteristic curve
Matric suction
Hydraulic hysteresis

1. Introduction

Rock fractures are formed through the failure of rock masses in shear, tension or a combination of both. Depending on the mechanical process producing the fractures and the type of rock, two different categories of fracture morphology may be observed: clean or open fractures, and gouge/mineral-filled fractures.[1] The clean fractures are those that are produced under tension, with no tectonic gouge or mineral precipitates between the fracture walls. The behavior of open fractures is affected by the interface properties of the rock fracture (e.g. the original fracture width, its roughness, fracture spacing and separation, deformability of fractures), the material properties of the surrounding rock, and the effective stress component that is oriented perpendicular to the plane of the fracture.[2–18]

The gouge/mineral-filled fractures on the other hand, are produced either as ductile shear zones or as once-open fractures later altered under shear or filled with precipitates.[1,19] The infill materials that occur between the walls of the fracture can be of different types (such as quartz, calcite, gypsum, coatings or filings of chlorite, talc, graphite or serpentine, and inactive or swelling clay materials), and significantly affect both fracture permeability and shear resistance. In this situation, the characterization of rock fracture behavior requires the consideration of a complicated interaction of morphological details of the fracture surface, combined together with the properties of the materials filling space between the rock layers.[15,20–27]

Even though literature on the mechanical behavior of the rock fractures with infill material is quite extensive, a rational framework has not been developed for assessment of the effects of stress state and degree of saturation of infill material on their shear behavior. Different degrees of saturation of rock or infill materials may occur in the fractures or fracture zones as a result of seasonal weather changes, ventilation of the cavern and subsequent evaporation of water or a pressure build-up in the gas phase during gas production. The surface tension and inter-particle contact forces in unsaturated infill materials arising from matric suction are expected to lead to variations in hydraulic and mechanical behavior of infilled rock fractures.[16,27–29] Specifically, it is hypothesized that trends in shear strength with stress state variables may be significantly different from those observed from fractures with saturated infills.

Indraratna et al. [27] utilized a high-pressure triaxial device to conduct a series of constant water content undrained triaxial tests on idealized saw toothed and natural silty clay-infilled fractures. The study aimed to assess the influence of the initial degree of saturation and thickness of the infill material on the shear strength of infilled fractures. The tests were performed by applying high stresses ranging from 300 to 900 kPa and degree of saturation

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http://dx.doi.org/10.1016/j.ijrmms.2016.07.001

varying between 0.35 and 0.85. Based on the results presented in this study, for thicknesses lower than a critical value, the shear behavior of infilled fractures were governed by the thickness of the infill material and interface characteristics of the fracture surface. However, for infill thicknesses exceeding this critical value, there was no significant change in strength with thickness increase and the infill material and its properties controlled the shear behavior of infilled fractures. Results also revealed the significant influence of degree of saturation of the infill material on the shear strength of the fractures. Based on experimental observations, an increase in both shear strength and dilation of the fracture was observed as the infill initial degree of saturation was decreased.

Although results by Indraratna et al. [27] revealed the significant influence of the degree of saturation on the shear strength of infilled fractures, the fracture specimens in this study were prepared by tamping the infill material to reach the same dry density but with different initial degrees of saturation. This situation is quite different from what occurs in the field, where the water content of the infill material routinely fluctuates with seasonal weather changes and reported results may not fully reflect the behavior of infilled fractures experienced in the field. Experimental observations by Kim et al. [30] revealed that the strength (in terms of G_{max}) of an unsaturated soil at a given degree of saturation for specimens prepared by controlling compaction moisture contents are smaller than those desaturated by controlling the matric suction. On the other hand, from the results of Indraratna et al.,[27] it is difficult to identify trends for the shear strength of infilled fractures during hydraulic hysteresis, when the infill material may experience different values of degree of saturation for the same level of suction, depending on whether the infill material experiences a drying or wetting path.[14,31] Different degrees of saturation result in different numbers of water meniscus between the particles of infill materials, affecting the inter-particle forces during drying and wetting paths. As a result, different trends of shear strength are expected for the infilled fractures upon drying and wetting.

This paper describes a new testing approach adapted to characterize the hydro-mechanical behavior of the infilled rock fractures during hydraulic hysteresis. The experimental approach developed in this study involves: (1) modifying a triaxial test device with the axis translation technique [32] for suction control, (2) a flow pump for the precise measurement of the infill degree of saturation, S_r, and (3) the digital image processing technique to measure the volume changes of the infill material and the fracture dilatancy during shear. The flow pump operates by moving a precisely machined circular piston into or out of a rigid steel water reservoir using a stepper motor. The stepper motor records the rotational position of the threaded rod, permitting accurate measurement of the flow volume into or out of the specimen. A pressure transducer incorporated into a suction-feedback control loop is also used to control the flow of water to or from the specimen and establish suction equilibrium conditions during the test.

2. Tested materials

The tested materials consist of two different types: a silty soil which is used as the material filling the space of the fracture, and Polyethylene material (Teflon) which is used as the material of the simulated rock fracture.

2.1. Fabrication of simulated fractures

One of the challenges in quantifying the contribution of infill degree of saturation and its stress state to hydro-mechanical behavior of infilled rock fracture is that both infill and rock materials are permeable and experience water volume change during the processes of saturation and desaturation. As a result, it may be difficult to isolate the contribution of the degree of saturation of each material to infilled fracture shear behavior. In this study, for reasons of simplicity, the rock fracture specimens are a series of undulating specimens fabricated in Polyethylene LDPE (Teflon). Similar approach was used by other researchers when investigating the behavior of infilled rock fractures during shear.[33] According to ASTM D570, the Polyethylene LDPE materials have a very low water absorption rate (less than 0.01% in 24 h) and can be described as impermeable. Some of the physical specifications of the Polyethylene LDPE materials are presented in Table 1.

Table 1
Physical specifications of the polyethylene LDPE materials.

Property	Tensile strength at 72 °F	Tensile modulus	Compression strength at 72 °F	Compression modulus
Standard	*D638*	*D638*	*D695*	*D695*
(MPa)	9.65	393	9.65	372.3

The fracture specimens are fabricated at a mean dip angle of 60° with the thickness of infill materials of 1.5 and 5.5 mm. They have a 55 mm diameter, fabricated in a way to maintain a 110-mm height after filling the fractures with the infill material of varying thickness. The fracture specimens have asperities with a height of 2 mm and an initial asperity angle of 20°. The provision of holes with diameters of 6 mm and 3 mm in the upper and lower halves of each Polyethylene specimen with the arrangements presented in Fig. 1 were made to saturate the infill material using the back-pressure technique and to ensure uniform application of air and water pressures during the desaturation process. In order to increase the continuity in the water phase between the infill material water, the water in the ceramic disk, and the water in the compartment below the ceramic disk during the suction measurements, an axially aligned cylindrical void with radius 40 mm and height 2 mm was created at the bottom of the lower half of the fracture specimen. The void was later filled with soil with characteristics similar to those of infill materials.

2.2. Properties of infill materials

The infill material is a natural silt obtained from the borrow

Fig. 1. Polyethylene specimen used as the rock fracture specimens.