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Effects of normal stress on water flow through a single rough-walled rock joint

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ABSTRACT

Water ingress to underground openings is one of the major concerns in mining and tunnelling, because, rock joints provide natural seepage paths for groundwater flow. To study the water flow through deformable rock joints, triaxial tests with water flow were conducted under various confining stress levels (0.7-5.0 MPa). Two tests were performed on fully mated fracture specimens, and three tests were performed on a non-mated specimen where the fractured surfaces were displaced by 2.0 mm at the start of the test. The results show that the volumetric flow rate decreases with the increase in the normal stress, but the decreasing rate of the flow rate tends to be smaller as the normal confining pressure increases. Similar tests were conducted on non-mated specimen to simulate typically mismatched rock joints. The actual values of flow rates of the three tests conducted on non-mated specimen were different from each other, but the trends in the data measured with the increase of the confining stress were similar. Together with mechanical aperture closure, the variation of hydraulic aperture were analysed based on cubic law, which shows similar changing trend with flow rate as confining pressure increases from 0.7 to 5.0 MPa. However, the closure of the mechanical aperture is much larger than corresponding hydraulic aperture variation due to rough fracture surface, approximately 10 times that of the hydraulic aperture in this experimental investigation.

Keywords: triaxial test, water flow, rock joint, flow rate, confining stress

1 INTRODUCTION

Fluid flow through jointed rock is of significant concern in many engineering applications, such as radioactive waste repository, geothermal extraction, dam foundations and underground openings, as fractures provide major pathways for water flow. In underground mining, tunnelling and other underground excavations, the water inflow increases the risk of inundation, and delays in construction caused by water ingress result in adverse consequences in terms of stability, productivity, and safety (Indraratna and Ranjith 2001, Jones 2009). The study of fluid flow through a single rock fracture, as a basic unit of the fracture network, is essential to understand the coupled hydraulic and mechanical behaviour of the fracture network system, which has attained great research interest in the past two decades (Makurat et al. 1990, Wei et al. 1995, Zimmerman and Bodvarsson 1996, Esaki et al. 1999, Li et al. 2008, Auradou 2009).

The flow characteristics of fractured rock are greatly influenced by the mechanical deformation. An increase in confining stress causes fracture closure to occur and the contact areas between the two surfaces to increase as the preferential flow pathway becomes more tortuous. Linear Darcy's law is conventionally assumed to be valid in hydro-mechanical behaviour of rock joints when laminar flow occurs. Then cubic law is derived by assuming the flow channel consists of two smooth parallel plates, which explicitly expresses the volumetric flow rate in terms of cubic hydraulic aperture (e^3). Gale (1990) demonstrated that the accuracy of measuring the residual aperture is critical for estimating hydraulic conductivity and fluid velocity. Indraratna et al. (1991) stressed the importance of aperture variation in flow behaviour, where in reality the aperture is rarely uniform. Zimmerman and Bodvarsson (1996) indicated that the cubic law can generally provide an acceptable prediction.

This paper provides an insight into the hydro-mechanical behaviour of single rough-walled rock fracture under normal confining stresses from 0.7 to 5.0 MPa. To simulate typically mismatched rock joints that are present in underground mines, triaxial tests with water flow were performed on both mated and non-mated specimens of fractured sandstone.

2 EXPERIMENTAL PROCEDURE

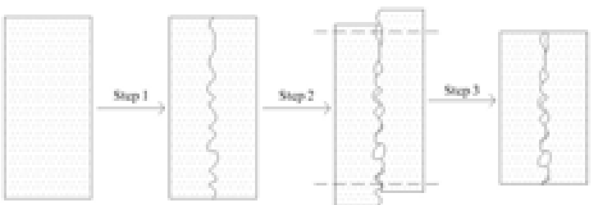
2.1 Specimen preparation

Sandstone, typical of the Illawarra region, Australia, was used to conduct triaxial tests with water flow. Intact cylindrical specimens (54 mm in diameter) were cored from sandstone block and then split into two halves (Figure 1(a)) using the Brazilian tensile technique. Mated specimen refers to the two halves of the fracture are fully matched, while the non-mated fractures refer to the two halves of the fracture are previously displaced by 2 mm to simulate mismatched joints in real mine environments. The extruding part of each half of the non-mated specimens was cut off and the ends were polished smooth with a lapping machine, as shown in Figure 1(b). The geometrical dimensions of the test specimens are summarised in Table 1.

Table 1 Geometrical dimensions of specimen

Specimen No.	Specimen Height mm	Fracture Width mm	Specimen type
1	97.23	53.70	mated
2	102.12	53.95	mated
3	95.42	53.98	non-mated

(a) fractured specimen



(b) non-mated specimen

Figure 1 Specimen preparation

2.2 Test set-up and procedure

The normal stress-flow coupling tests were conducted on the fractured sandstone using the Two-phase High-pressure Triaxial Apparatus (TPHPTA), schematically illustrated in Figure 2. The tests focused on the hydro-mechanical behaviour of a single rock fracture so that the two aspects could be closely studied. After each end was lapped smooth, the specimen was wrapped in a polyurethane membrane and placed on the bottom seating of the triaxial cell. The membrane was then clamped to the top and bottom seat with two horseshoe clamps so that no confining oil leakage would occur during the test. A high-strength plastic tube was used inside the triaxial cell to carry water flow from the top of the specimen to the outlet. A constant pressure hydraulic pump was used to raise the pressure of the silicone oil inside the cell to the desired value. The water was pressurised by compressed air and then fed to the test specimen through a specially designed porous platen, which distributed the flow evenly over the width of the whole fracture. To prevent air from dissolving in water, a high-strength rubber bladder was used inside the water vessel to separate the water from compressed air (Figure 2). In order to measure the normal deformation of fracture under various confining pressure, a pair of fibre optical sensors were mounted through the side wall of the triaxial cell. A small square piece of aluminium foil was pasted on each monitoring point of the membrane to improve the optical reflectivity and hence precision. The inlet and outlet water pressure, confining oil pressure, and normal deformation of the specimen were carefully monitored using an automated computer controlled data acquisition system. The volumetric flow rate was measured manually by weighing the collected water against the time. During the test, the water pressure was always kept lower than that of the confining (oil) pressure by 200 kPa to prevent specimen collapse due to water pressure.

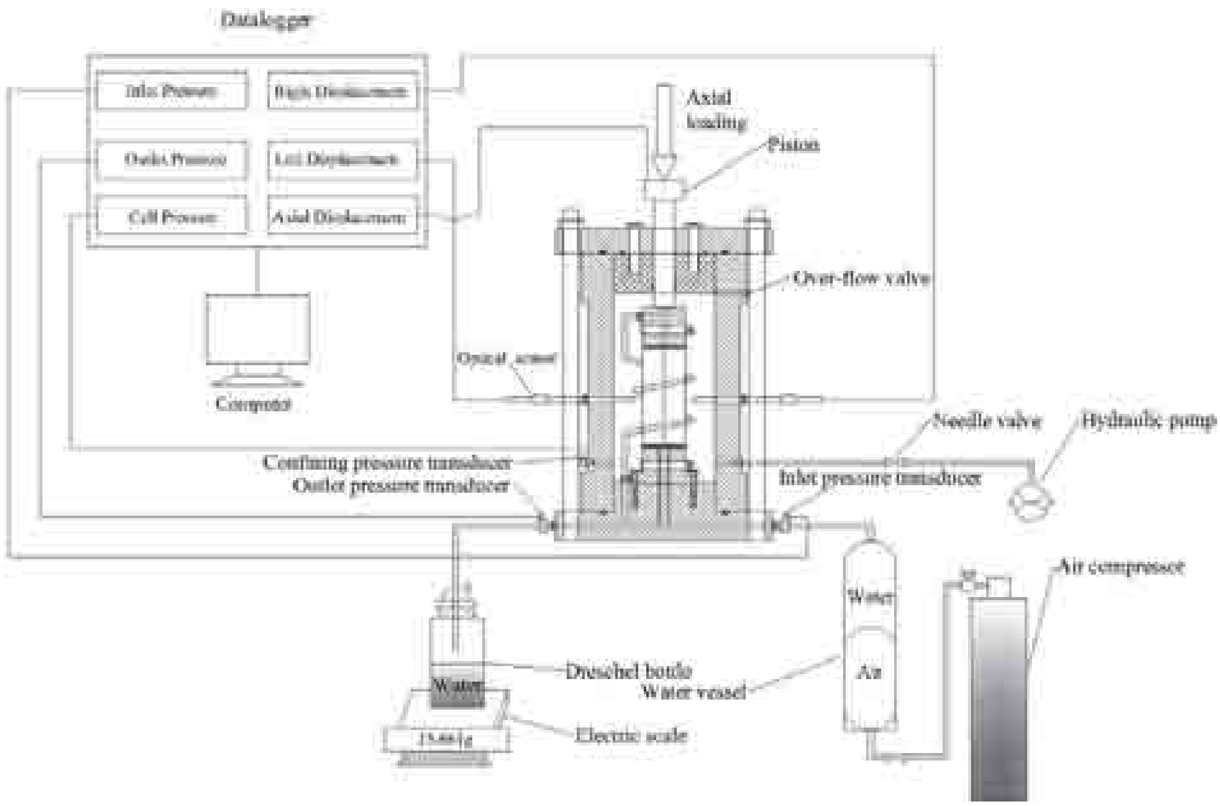


Figure 2 Schematic illustration of the triaxial set-up

In the study of hydro-dynamics, the Reynolds number (R_e) is extensively used to demark different flow patterns, and is mathematically expressed by:

$$R_e = \frac{V \rho D_h}{\mu} \tag{1}$$

where V is the mean velocity of water flow, ρ is the water density (1000 kg/m^3), μ is the dynamic viscosity of water that is equal to 1.0×10^{-3} N·s/m^2 at 20˚C and D_h is hydraulic diameter, which is twice the hydraulic aperture e, when considering a flow length $L >> e$.
Macroscopically, the mean flow velocity is expressed by:

$$V = \frac{Q}{A} \tag{2}$$

where Q is the flow rate, A is flow area and $A=we$, in which w is the width of the fracture.
Substituting Equation (2) into (1), the Reynolds number can be rewritten as:

$$R_e = \frac{\rho Q}{w\mu} \tag{3}$$

In this study the maximum R_e measured for mated and non-mated specimens was less than 14 and 107, respectively, which was much less than the critical value for turbulent flow (Zimmerman and Bodvarsson 1996). Hence, the water flow could be considered as laminar.

3 RESULTS AND DISCUSSION

To closely study the hydraulic and mechanical behaviour of a single fracture, the test results were analysed in two different ways: (a) the flow rate vs. confining stress, and (b) the aperture change vs. confining stress.

3.1 Mated specimen

Figure 3 shows the variation of volumetric flow rate as a function of confining stress for the two mated specimens. It can be seen that the flow rate initially decreased sharply with an increase in confining stress from 0.7 to 3.0 MPa, and then it stabilised when the confining pressure approached 5.0 MPa. The change in flow rate reflects the closure of the fracture aperture. Assuming the validity of cubic law that simplifies the flow channel consisting of two parallel plates, the hydraulic aperture *e* can be calculated by:

$$e = \left(\frac{12\mu Q}{w\left({}^{dp}\!/_{dx} \right)} \right)^{1/3} \tag{4}$$

where *dp/dx* is the pressure gradient and macroscopically equal to $(p_i\text{-}p_o)/L$, where p_i is the inlet pressure, p_o is the outlet pressure, and *L* is the length of the flow path.

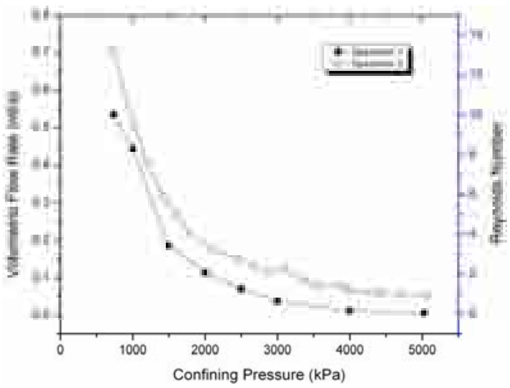
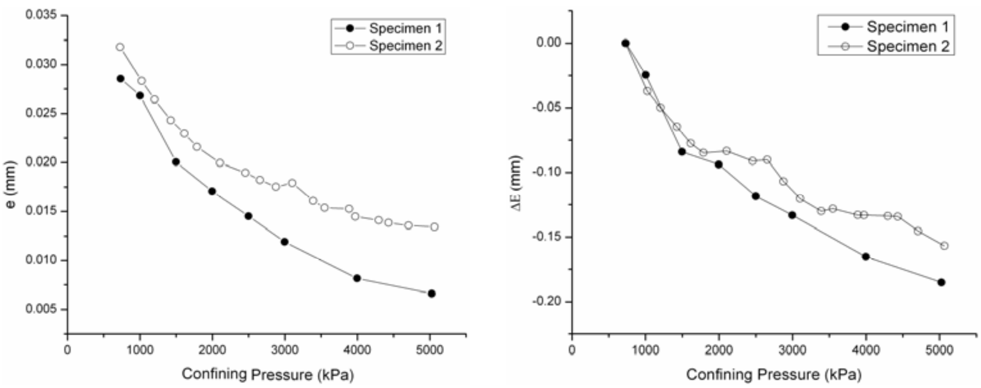


Figure 3 volumetric flow rate against the confining pressure for mated specimens



(a) (b)

Figure 4 Hydraulic aperture and mechanical aperture closure of mated specimens

The hydraulic aperture *e* and the closure of the mechanical aperture ΔE are illustrated in Figure 4 as a function of confining pressure. It can be seen that the hydraulic aperture *e* decreased with the increase in confining pressure, following exponential trend. The decreasing rate in hydraulic aperture becomes smaller with the increase of confining stress. The mechanical aperture closure, as shown in Figure 4 (b), follows a similar trend with the hydraulic aperture. However, comparing the variation of hydraulic aperture and the mechanical aperture showed that the closure of mechanical aperture is much larger than that of the equivalent hydraulic aperture due to fracture unevenness (roughness). In this study case, the mechanical closure is approximately 10 times of hydraulic aperture variation.

3.2 Non-mated specimen

Three tests were performed on the non-mated fracture specimen, and the flow rate of each test is shown in Figure 5. Even though the same specimen was used, three tests showed distinctly different flow rates under the same confinement. This probably occurred, because each half of the specimen moved slightly away from their original position when they were set in the triaxial cell. However, the flow rate is of the same trend with the increase of the confining stress, which initially decreased at a higher rate when the confining stress increased from 0.7 to 1.0 MPa, and then the decreasing rate gradually tends to be smaller as the confining pressure increased up to 5.0 MPa. When compared to the mated case, it can be seen that the flow rate magnitude of the non-mated specimen was much higher, probably due to the dilated aperture (riding over asperities).

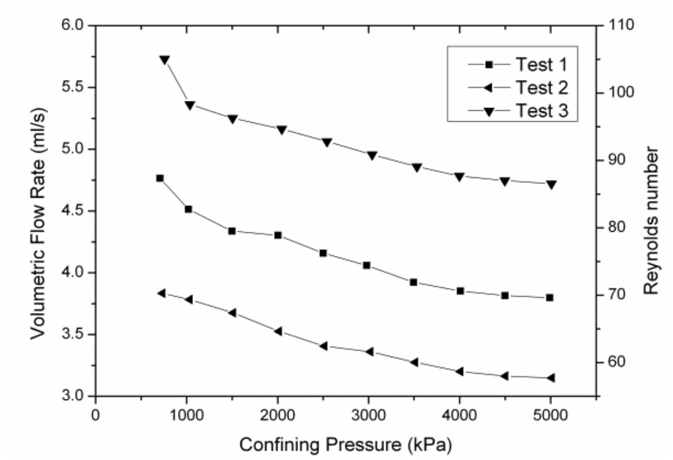


Figure 5 volumetric flow rate against the confining pressure for non-mated specimen

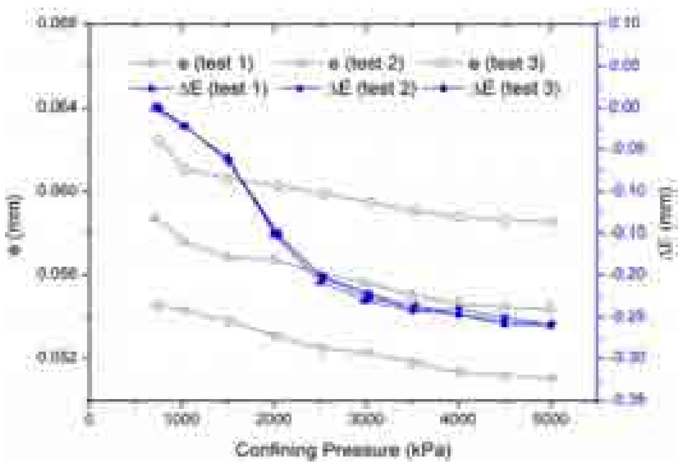


Figure 6 Closure of mechanical and hydraulic aperture for non-mated specimen

The hydraulic apertures for each test were calculated using the cubic law defined in Equation (4), and the results were illustrated in Figure 6, together with closure of the mechanical aperture. It can be observed that the normal closures of the three tests are of the same trend, even though the original matching state of the two fractured halves was slightly different. The total normal closure Δe and ΔE were equal to 0.03 mm and 0.26 mm, respectively, when the confining pressure increased from 0.7 to

5.0 MPa. Similar to the variation trend of the flow rate, the decreasing rate of hydraulic aperture tends to be smaller with the increase in confining pressure from 0.7 to 5.0 MPa. On the other hand, comparing Figure 4 with Figure 6 shows that the total amount of fracture closure of the non-mated specimen was slightly larger than the mated specimens. This was probably due to the reduced contact area between the non-mated specimen halves when compared to the mated case.

4 CONCLUSIONS

Rock joints provide natural flow pathways for groundwater. This study experimentally investigated hydraulic and mechanical behaviour of tensile sandstone fracture by conducting triaxial tests with water flow. It provides an insight for understanding and predicting the ingress of water into an underground excavation and for assessing the associated risk of inundation.

To study the hydraulic behaviour of the matched and mismatched rock joints which commonly exist in engineering field, both mated and non-mated specimens of jointed sandstone were used to perform triaxial tests with water flow under the confining pressure 0.7-5.0 MPa. Non-mated joints were simulated by the two fracture halves of the specimen being slightly displaced at the start of the test to study typically mismatched rock joint in field. The laboratory triaxial tests reported here indicate that the volumetric flow rate for both mated and non-mated fractured specimens decreased when the normal stress increased from 0.7 to 5.0 MPa. The rate of decrease tends to smaller as the confining pressure increased from 0.7 to 5.0 MPa. The magnitude of the mechanical aperture closure is much larger than that of hydraulic aperture variation due to rough fracture surface.

For three non-mated joint tests, even though the same specimen was used with different degree of joint mismatch, the flow rates were different from each other, and naturally different to the mated joint specimens. However, all the flow rates showed similar trends where the data plots were shown to become almost parallel to each other. Despite the difference in initial fracture displacement, both the magnitude and trends of the mechanical aperture closure were similar for the three non-mated tests. As expected, the flow rate and total closure of mechanical aperture of non-mated specimen were higher than that of the mated specimen, because of the greater joint aperture due to non-mated displacement.

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