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Full Length Article

An approach to measure infill matric suction of irregular infilled rock joints under constant normal stiffness shearing

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A B S T R A C T

Rock joints infilled with sediments can strongly influence the strength of rock mass. As infilled joints often exist under unsaturated condition, this study investigated the influence of matric suction of infill on the overall joint shear strength. A novel technique that allows direct measurement of matric suction of infill using high capacity tensiometers (HCTs) during direct shear of infilled joints under constant normal stiffness (CNS) is described. The CNS apparatus was modified to accommodate the HCT and the procedure is explained in detail. Joint specimens were simulated by gypsum plaster using three-dimensional (3D) printed surface moulds, and filled with kaolin and sand mixture prepared at different water contents. Shear behaviours of both planar infilled joints and rough joints having joint roughness coefficients (JRCs) of 8–10 and 18–20 with the ratios of infill thickness to asperity height (t/a) equal to 0.5 were investigated. Matric suction shows predominantly unimodal behaviour during shearing of both planar and rough joints, which is closely associated with the variation of unloading rate and volumetric changes of the infill material. As expected, two-peak behaviour was observed for the rough joints and both peaks increased with the increase of infill matric suction. The results suggest that the contribution of matric suction of infill on the joint peak normalised shear stress is relatively independent of the joint roughness.

1. Introduction

Rock joints, in particular those filled with compacted sediments, are the most common geological structures that can contribute to a drastic reduction in the stability of rock masses. The key factors affecting the joint shear behaviour include joint roughness, type and thickness of joint infill, stress history and water content of infill (Barton, 1978, 2013; Lama, 1978; Phien-wej et al., 1990; de Toledo and de Freitas, 1993; Papaliangas et al., 1993; Pellet et al., 2013). In some cases, infilled rock joints are located above the groundwater table, and thus matric suction of the infill material can play a significant role in the joint shear behaviour (Khosravi et al., 2013, 2016; Indraratna et al., 2014). Furthermore, below groundwater table, partially saturated conditions may also occur for infilled joints in drained strata adjacent to deep underground mine excavations (Tsang et al., 2005; Matray et al., 2007).

While the influences of water content and humidity conditions on the shear behaviour of infilled rock joints have been recognised in the past by introducing empirical parameters such as joint water reduction factor (J_w) in estimation of the joint shear strength (e.g. Barton et al., 1974), the role of unsaturation was conveniently ignored. More recently, Alonso et al. (2013) studied the influence of matric suction on the shear behaviour of rock joints without infill. Zhang (2017) examined the effective stress in clay rock theoretically and experimentally from unsaturated to saturated conditions. Indraratna et al. (2014) conducted a series of constant water content (CW) triaxial tests on infilled rock joints, considering the initial matric suction of infill for predicting the peak shear strength. Khosravi et al. (2016) further studied the shear behaviour of rock joints infilled with unsaturated silt, maintaining constant suction conditions using axis translation technique. Although this approach is well established for investigating unsaturated soil behaviour, it may not truly represent field conditions, where air pressure is atmospheric and water pressure is negative.

Furthermore, the influence of matric suction of the infill material on the joint shear behaviour has been only appreciated for in constant normal load (CNL) direct shear or traditional triaxial shear,

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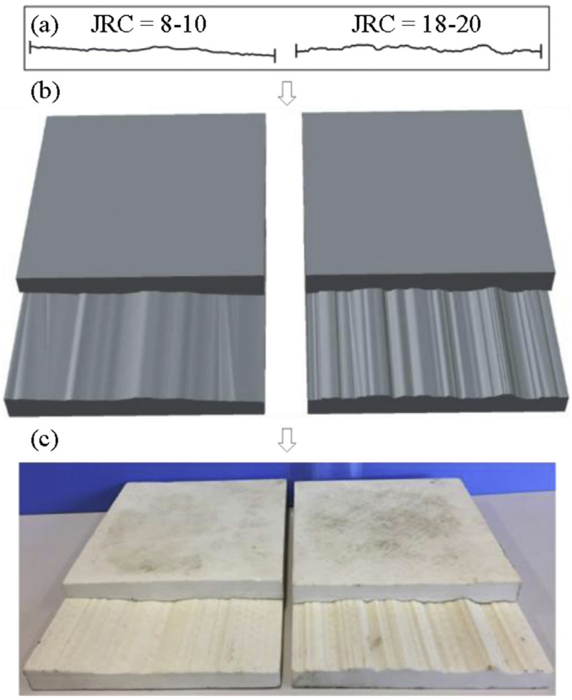

Fig. 1. 3D printing procedure for Barton's joint moulds: (a) Barton's standard joint profiles for $JRC = 8-10$ and 18–20, respectively (Barton and Choubey, 1977); (b) 3D CAD model used for the joint profiles; and (c) Printed joint moulds.

but in some cases, the in situ rock joints are more likely to experience constant normal stiffness (CNS) conditions (Indraratna et al., 1998). Moreover, the difference between CNS and CNL envelopes can be properly quantified only if the stress state variables can be measured, in which the role of pore water pressure and matric suction developed upon shearing was incorporated when significant volumetric strains occurred within the compacted infill. In addition, the effects of asperity attrition and over-compaction of infill within rough joints and their implications on the apparent shear strength have been highlighted by Indraratna et al. (2005, 2010a), but these models could not capture the role of suction. Therefore, Indraratna et al. (2014) proposed a constitutive model that could capture the effect of initial matric suction, but this model suffered from not being able to interpret the influence of suction variation with the shear displacement of a rough joint with compacted infill. During shearing, the average aperture between coupled joint surfaces varies, which leads to changes in the patterns of void ratio and degree of saturation within the infill layer, causing the fluctuation of the matric suction (Romero Morales, 1999; Rahardjo et al., 2004; Thu et al., 2006). This paper introduces an approach for directly measuring the matric suction of the infill material within the shearing joints using high-capacity tensiometers (HCTs) while maintaining the CNS load conditions. The purpose is to investigate the variation of matric suction of joint infill during shearing and its influence on the shear behaviour of irregular joints with compacted infill, so that the peak shear strength can be predicted more accurately.

2. Materials

2.1. Infill material

In this study, a mixture of fine sand (25%) and commercial kaolin (75%) was selected as the infill material. The index characterisation of the infill material reported in Indraratna et al. (2014) showed that the material has a liquid limit of 39% and plasticity index of 19. In addition, effective internal friction angle (ϕ') of 21° and cohesion (c') of 13.4 kPa were obtained in consolidated undrained (CU) triaxial tests. The required water content was added to the infill material and the samples were kept in constant humidity and temperature conditions for at least one week for moisture equilibration.

2.2. Simulated irregular rock joint specimens using three-dimensional (3D) printing

To accurately replicate the behaviour of rock joints in laboratory, typically artificial joint specimens are adopted rather than natural jointed specimens. The joint models ensure repeatability of the geometric profiles used for various tests. In this study, an innovative technique based on 3D printing was adopted for

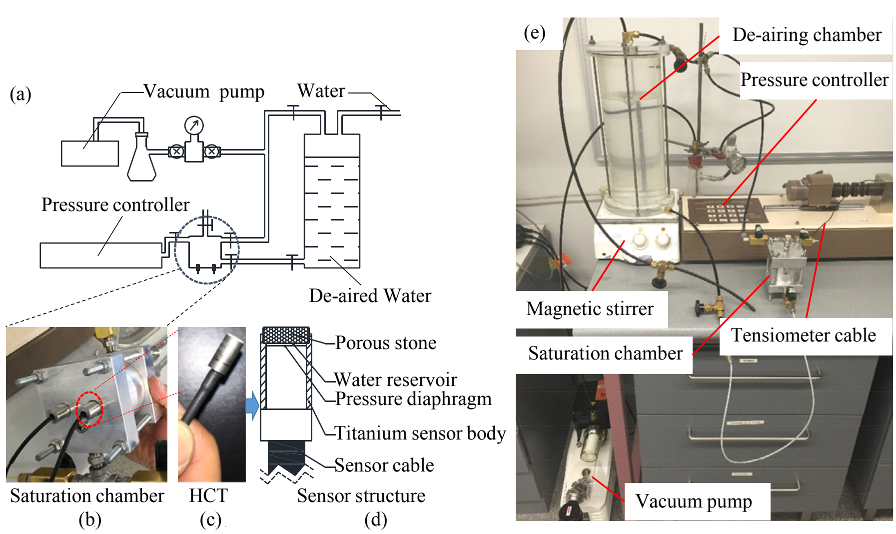

Fig. 2. Saturation system for the HCTs: (a) Schematic illustration of the saturation system; (b) Saturation chamber; (c, d) Detail of HCT-sensor; and (e) Photograph of the whole saturation system.

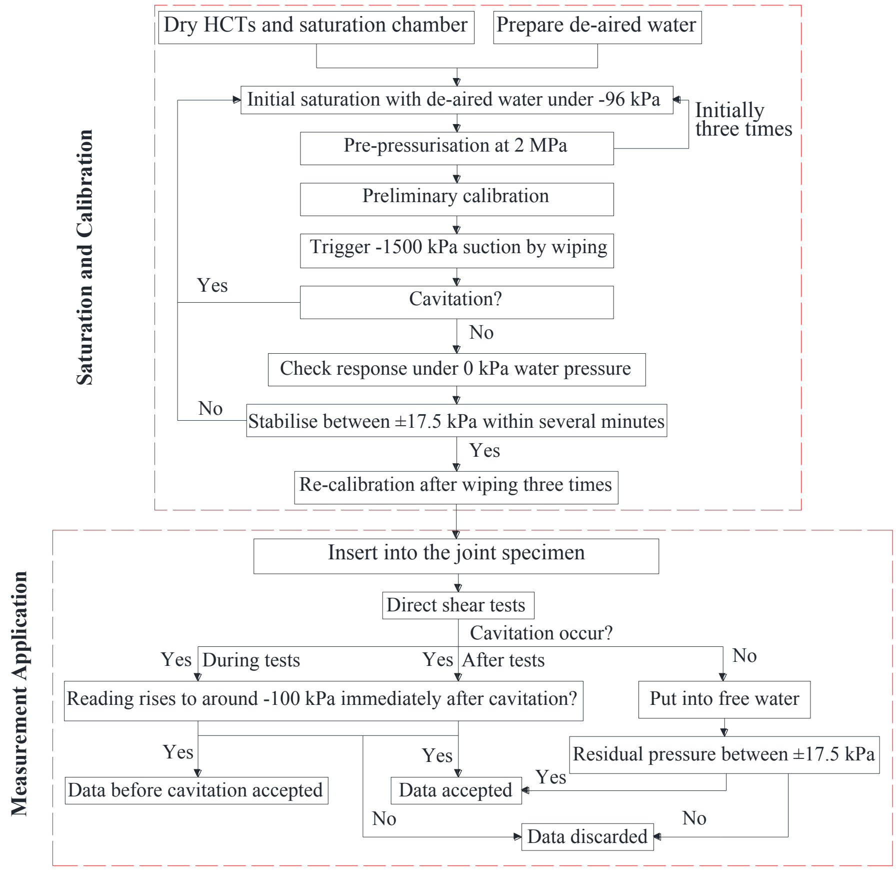

Fig. 3. A simple flowchart for the saturation procedure, calibration and measurement with the HCTs.

generating rough joint moulds with specific profiles due to its precision and efficiency, and simplified two-dimensional (2D) irregular joint moulds were employed to prepare the joint specimens (see Fig. 1). Two different profiles selected from the standard joint roughness profiles (Barton and Choubey, 1977) were considered, having joint roughness coefficients (JRCs) of 8–10 and 18–20, respectively.

The replicated joint specimens were square with dimensions of 120 mm × 120 mm. The 3D printed joint moulds were then used to make joint specimens using high strength gypsum plaster ($CaSO_4$

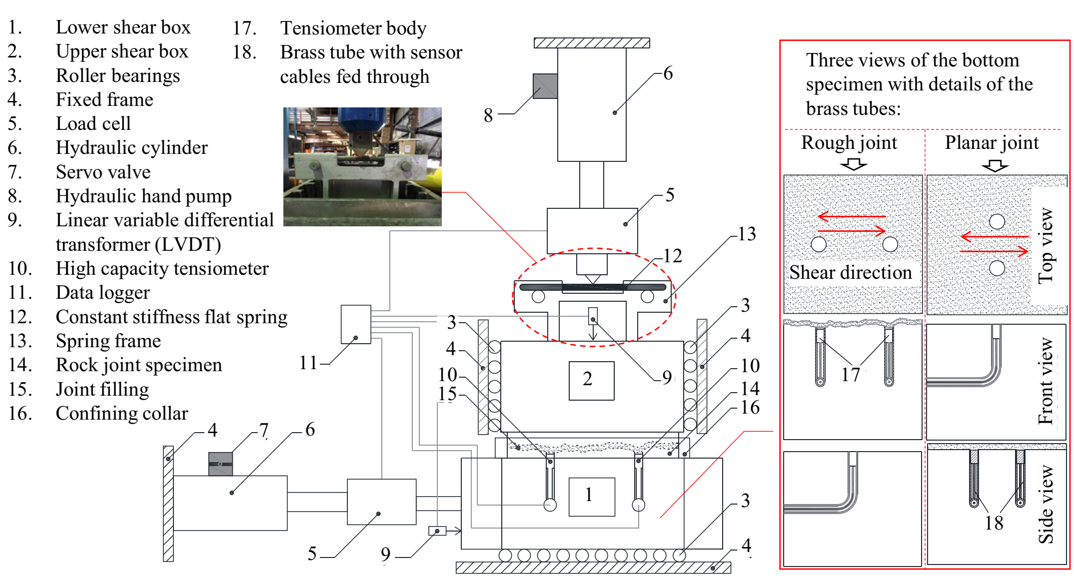

Fig. 4. Schematic diagram of the shear apparatus with the measurement of infill matric suction (modified after Indraratna et al., 1998).

hemihydrate, 98%) mixed with water at a ratio of 7:2 (gypsum plaster: water) by weight, mimicking a soft sedimentary rock (Indraratna, 1990). The top and bottom joint specimens were cast with dimensions of 120 mm × 120 mm × 150 mm and 120 mm × 120 mm × 100 mm, respectively. In addition, to facilitate the access of a HCT to the joint shear plane, two machined brass tubes were used. The prepared brass tubes were specially machined so that the HCTs can be seated inside, with the ceramic stone approximately 0.5 mm lower than the bottom of joint surface. In order to minimise air entrapment during casting, the moulds were vibrated mildly during preparation. Subsequently, the specimens were left for an hour to harden before being removed and cured under a controlled temperature of 45 °C for two weeks. Apart from rough joint specimens, planar joints were also cast for comparison.

After curing, the surfaces of joint specimens were sealed with an organic waterproof sealant, and then fully saturated to minimise water exchange between the gypsum and the infill material during compaction and shearing. An extra collar was attached to the bottom shear box around the infill specimen, to assist in the compaction of the infill material by preventing the soil from squeezing out. After placing the HCTs into the brass tube ends below the joint surface, the infill material of a required thickness was spread uniformly over the joint surface within the collar. The bottom and top boxes were then placed into the shear apparatus, and the infill between the coupled joint surfaces was statically compacted.

3. Testing program

3.1. Measurement of matric suction

In this study, two HCTs were adopted to directly measure the variation of infill matric suction. A pore-water pressure transducer with a high air entry (15 bar, 1 bar = 0.1 MPa) ceramic tip capable of measuring negative pore water pressures (i.e. EPB-PW from Measurement Specialties Ltd.) was used. This type of transducer was selected because of its miniature dimension (6.4 mm in diameter) and robust sensor body (titanium casing) that could withstand possible large lateral stresses applied during compaction and shearing without sustaining damage.

Before installing the HCTs into the infilled joint specimens, rigorous saturation of the HCTs was conducted. The saturation chamber designed and the steps adopted for saturating the HCT were based on the procedures outlined in past studies (e.g. Ridley and Burland, 1993; Meilani et al., 2002; Take and Bolton, 2003; He et al., 2006). The saturation chamber consisted of the vacuum system (a JAVAC double-stage high vacuum pump, with the gauge having accuracy of 2 kPa), the pressurisation system (2 MPa GDS instrument water pressure controller with accuracy of 1 kPa), the saturation chamber, and the de-airing chamber. The tensiometers were embedded to the bottom of the saturation chamber through two Swagelok adapters. The schematic and the photograph of the saturation system are shown in Fig. 2. The saturation procedure included a number of cycled vacuum and pre-pressurisation stages (a minimum of 3 cycles) and subsequently, the HCT readings were calibrated for positive water pressures and saturation quality was checked by examining whether cavitation occurred upon sustaining a suction close to 15 bar while drying. In order to prevent evaporation-induced cavitation, the HCT ceramic tip was covered by kaolin wet paste during installation in the direct shear apparatus. In addition, a very thin layer (<0.5 mm) of wet paste was applied to ensuring good contact between the ceramic tip and the infill material (Boso et al., 2004). The calibration was checked in the beginning of each test for eliminating possible shift of calibration line. The procedure adopted is outlined in the flowchart, as shown in Fig. 3.

3.2. CNS direct shear apparatus with measurement of matric suction of infill

The existing CNS shear apparatus (designed and built at the University of Wollongong (Indraratna et al., 1998)) was modified for allowing the continuous measurement of matric suction of infill material during in situ compaction and shearing. Schematic illustrations of the apparatus and joint specimens are shown in Fig. 4.

4. Results and discussion

4.1. Compaction and water retention behaviours

In order to maintain the initial compaction stress state during shearing, a range of specimens having different water contents were statically compacted in the CNS apparatus. Fig. 5a shows the static compaction data under a normal stress of 0.5 MPa, as well as the

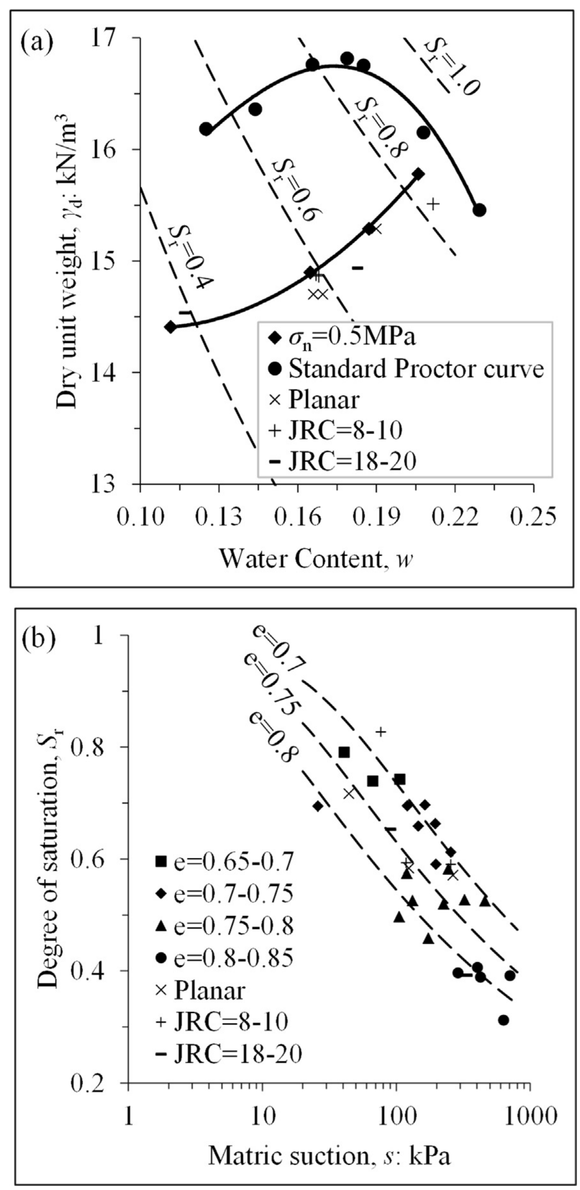

Fig. 5. (a) Compaction data and (b) associated water retention. Initial conditions of the infill material for the shear tests are noted. *e* represents the void ratio.

standard Proctor compaction curve (following Australian Standards 1289.5.1.1) for comparison. The most striking aspect is that a wet side was not observed for the static compaction curve. This might not correspond to the intuitive behaviour first expected, but several other studies on statically compacted kaolin have reported similar behaviour (Venkatarama-Reddy and Jagadish, 1993). Furthermore, Tarantino and Tombolato (2005) indicated that a wet side could only be achieved for statically compacted specimens prepared at water contents larger than the corresponding air-entry suction water content. In this range, the air phase is occluded (bubbles), and pore water pressure increases during compaction thus preventing a volume decrease. The results of the associated water retention behaviour (Fig. 5b) suggest that all specimens were compacted for suctions larger than the air-entry value and thus typically representative of the dry side of optimum moisture content.

4.2. Infilled joint shear behaviour

A series of CNS shear tests was carried out on both planar and rough joints (JRC = 8–10 and 18–20), with initial normal stress of 500 kPa, and infill water contents ranging from 11.7% to 21.2%. For rough joints, the ratios of infill thickness to joint asperity height (t/a) were kept as 0.5, with asperity heights of 2.94 mm and 3.94 mm for joints with JRC = 8–10 and 18–20, respectively.

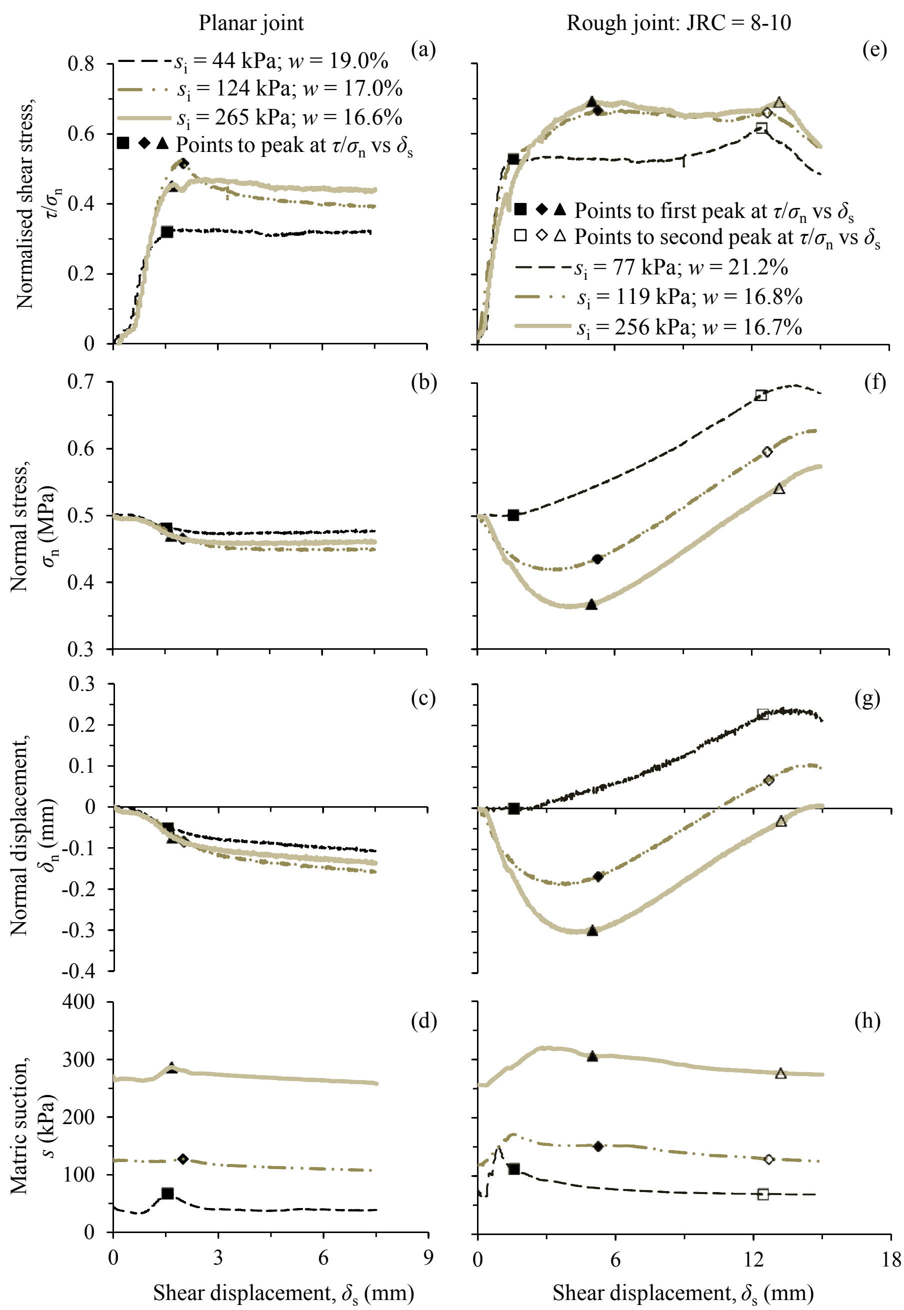

Fig. 6. Effects of water content and matric suction of the infill material on the joint shear behaviour for (a–d) planar and (e–h) rough joints (JRC = 8–10). Peak normalised shear stress $(\tau/\sigma_n)_{peak}$ values are plotted as markers and for rough joints, the first peaks are plotted as solid symbols, while the second peaks are using open symbols.

The infilled joints shearing behaviour of planar and rough joints (*JRC* = 8–10) prepared at approximately the same infill material water content and suction are shown in Fig. 6a–d and e–h, respectively. As the normal stress (σ_n) varies with joint dilation or compression during shearing due to CNS condition (Indraratna et al., 2005), the relationships between the normalised shear stress (τ/σ_n, i.e. mobilised friction), normal stress, normal displacement (δ_n) and matric suction (s) of joint infill for different horizontal displacements (δ_s) are plotted.

For planar joints, the shear stress reaches peak after moving a distance about 2 mm, then decreases to a residual state (Fig. 6a). The infill layer was exhibiting mainly compression status throughout the shearing stage (Fig. 6c) as the infill material was extended towards two sides that were not confined along the shear direction. As expected, the normal stress tends to decrease as well (see Fig. 6b); however, it remains stable once a horizontal displacement of 3 mm is exceeded whereas the normal displacement continues to decrease in this range.

Fig. 6c shows the variation of matric suction (average of the 2 HCT measurements) of the joint infill material during shearing. The curves exhibit a clear peak at the position corresponding to peak normalised shear stress ($(\tau/\sigma_n)_{peak}$) (Fig. 6a) and seem sensitive to changes both in normal stress and volume. This is illustrated in Fig. 7 where the relationship between the unloading rate and the matric suction variation during shearing is shown. It can be observed that in the range of $\delta_s < 4.5$ mm, the variation of matric suction correlates well with the unloading rate. After $\delta_s > 4.5$ mm, the normal stress becomes stable and the incremental variation is marginal, but suction continues to decrease. In this range, the matric suction variation can be correlated with the normal displacement trends (compression or equivalent increase in degree of saturation).

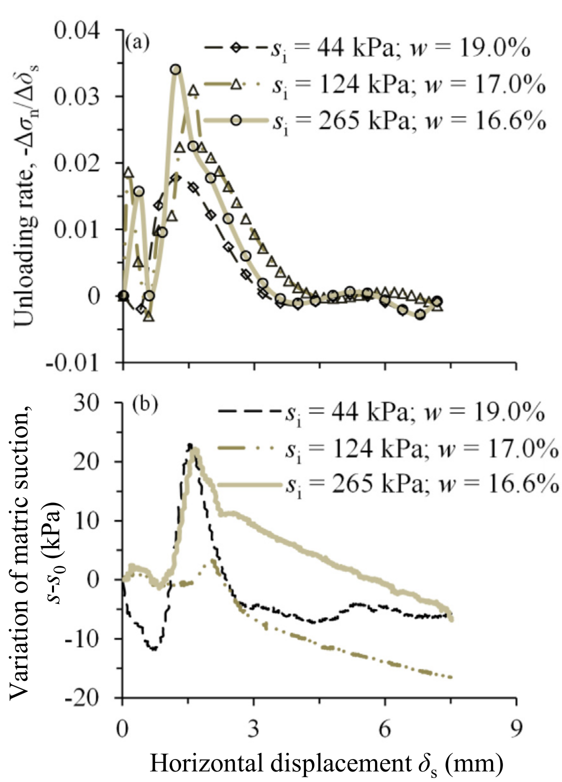

Fig. 7. Test results for planar joints in terms of the variations of (a) unloading rate ($-\Delta\sigma_n/\Delta\delta_s$) and (b) matric suction of infill during shearing.

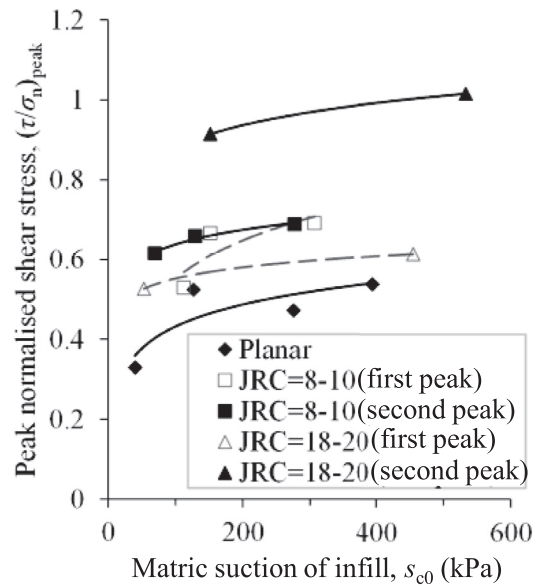

Fig. 8. Peak normalised shear stress $(\tau/\sigma_n)_{peak}$ with corresponding matric suction of infill s_{co}.

Fig. 6e–h shows selected test results of infilled simulated rock specimens with JRC of 8–10. Only one tensiometer reading was obtained for these tests, as the other one malfunctioned during the shearing stage.

As the t/a ratio is smaller than unity, a two-peak behaviour is observed in the results for different initial water contents and matric suctions. In the relationship between τ/σ_n and δ_s as shown in Fig. 6e, the shear behaviour before first peak (black symbol) was mainly controlled by the infill layer; after the first peak, the shear stress increased gradually as the joint asperities came to contact. The rock interference (second peak) then governed the overall shear behaviour, as in this range, the τ/σ_n value is nearly parallel (Indraratna et al., 2010b).

Two peaks were also observed in the normal stress, normal displacement and matric suction curves. Before the first peak, the infilled joint was “compressed” as shown in Fig. 6g, leading to a slight decrease of the normal stress (Fig. 6f). After the first peak, significant dilation occurred due to the joint interference (Fig. 6g) and there was an increase in the normal stress (Fig. 6f). Similarly to the trends observed for planar joints, the infill matric suction shows a predominant peak that can be associated with both variations in normal stress and volume during shearing (Fig. 6h). Note that for these joints, the infill material in the interfering area of the joint plane was squeezed significantly under high concentrated normal stress, which may account for the gradual decrease in matric suction after the first peak (Fig. 6h) accompanied with the increase of joint dilation.

By comparing Fig. 6d with Fig. 6h, it can be observed that the variation in matric suction in infilled rough joints (>50 kPa) was more significant than that of infilled planar joints (<25 kPa). This may be due to the significant unloading in terms of normal stress during shearing of rough joints, compared with that of planar joints. It also indicates that consideration of constant matric suction during shearing of the rough joints may not always be appropriate; however, further studies with a variety of t/a ratios, HCT locations and JRC profiles are required to accurately map the cases where matric suction variation during shearing is likely governing the behaviour of the infilled rock joint.

4.3. Peak normalised shear strength

Fig. 8 represents the relationship between peak normalised shear stress $(\tau/\sigma_n)_{peak}$ and corresponding matric suction of infill material for the three types of rock joints. The second peak (rough joints) and peak (planar joints) normalised shear stresses all show an increase with the increase of matric suction of infill, although the peak values increase much more significantly with joint roughness (JRC increasing from 0 to 8–10 to 18–20). This indicates that joint roughness controls the second peak of rough joints, while matric suction of infill has a secondary effect. It is also clear that the first peak values (typically governed by the infill behaviour) of τ/σ_n of both types of rough joints converge under higher suctions, but are still slightly higher than those of planar joints.

In addition, it seems that the curves corresponding to the second peak of τ/σ_n are parallel, which may indicate that the JRC only influences the intercepts of these curves. This is reasonable as typically matric suction strength functions consider a cohesion intercept in the shear strength model (Miao et al., 2001; Indraratna et al., 2014).

5. Conclusions

This study proposed an approach for directly measuring matric suction of a compacted infill material inside a rock joint under CNS shearing conditions. The existing CNS apparatus was modified to accommodate two HCTs in the lower shear box and the HCT saturation system was designed. Selected joint specimens were cast using 2D extruded surface moulds obtained using 3D printing, and a pair of brass tubes specially machined was left in the simulated rock specimen to facilitate the HCTs access to the joint shear plane.

Tests were conducted at constant water contents for both planar and rough joints. Due to the CNS loading condition, test results were analysed compared to the traditional CNL conditions. The normalised shear stress at peak was analysed rather than the shear stress. A relationship was observed between the unloading rate and the variation of matric suction of infill during planar joints shearing. Although the infill matric suction shows a similar predominantly unimodal behaviour for both planar and rough joints, the mechanism may be different due to the changes in normal stress and volume caused by joint asperities.

The results show that there is an increase of peak normalised shear stress with the increase of matric suction of the infill material. However, compared with the impact of joint roughness, this influence is secondary, particularly for the second peak of normalised shear stress. In contrast, the joint roughness has little effect on the first peak compared with the influence of matric suction of infill.

The evaluation of the variation of infill matric suction during joint shearing is important for predicting the peak shear strength in jointed rock engineering practice. Typically the additional shear strength derived from the infill matric suction provides a cohesion intercept in the peak shear strength–normal stress envelopes of infilled joints (Indraratna et al., 2014). The accurate evaluation of the matric suction during shearing is essential to capture the real peak strength envelope. Hence it is important to establish a function between infill matric suction and shear displacement. Although the suction variation trends were only studied qualitatively in this paper, the observed unimodal behaviour and the relationships between unloading rate and suction variation could give reference to future mathematical modelling under CNS conditions. Furthermore, the role of joint profile, location of HCT, t/a ratio and initial normal stress on the variation of matric suction of infill material needs to be examined in detail.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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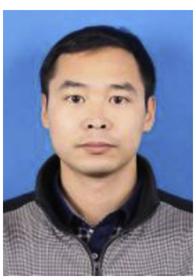

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