Effect of Infill Moisture Content and Thickness on Shear Behavior of Planar and Rough Rock Joints

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ABSTRACT: The shear behavior of rock joints have normally been investigated in the past by conducting conventional direct shear test in the laboratory, where during the shearing process, the effect of infill material is often neglected.
It is well known that the shear strength of rock joints decreases significantly due to the presence of gauge on infill materials. In addition, the joint strength is highly dependent on the shear behavior of infill material and joint asperity during shear movement. Though many researches have been done about the influence of infill material and asperity on joint shear strength, however, only a limited number of studies are found in relation to the influences of infill thickness and water content on the shear strength of infilled rock joints. The current study is an attempt to investigate the shear behavior of soft rock joints under Constant Normal Load v (CNL) conditions, with special reference to the influences of infill thickness and moisture content on shear behavior of planar and rough joints. The results of this study show that infill water content could influence shear strength of planar and rough rock joints, more significant than infill thickness.

KEYWORDS: Rough rock joints, Shear behavior, Infill, Moisture.

1. INTRODUCTION

Various geological types have a strong relationship with slope development under certain geological conditions, such as unstable dip slope consisting of bedded sedimentary rocks with bedding planes. Slope failure that killed 28 persons and destroyed 80 houses in Lincoln community at northern Taiwan triggered by heavy rainfalls during typhoon Winnie is an example.

The shear resistance of rock joints is dependent on a great number of geological factors, such as the state and properties of the surrounding rocks, the undulation of the joint walls, the degree of their degradation by weathering and other geological processes, the composition and properties of the joint filling, joint width and filling thickness, degree of joint roughness, stress state of the rock mass and other factors (Fishman, 2004). Based on the results of 156 field large-scale shear tests, carried out at 32 various geological sites, Fishman (2004) had shown that, despite the large variety of investigated rock mass discontinuities, there is a dependence of the shear coefficient on discontinuity width and amplitude of discontinuity roughness in relation to filling thickness. Geetsema (2002) also proved that the shear strength of planar joints in mudstone under saturated conditions are much lower than was expected and this phenomenon should be taken into consideration in the design of dams on mudstone similar rock types with planar joints.

The shear properties of filling in its natural state were studied in rare cases in view of the difficulty, and more often in view of the impossibility, of undisturbed filling sampling. Therefore, the shear behavior of rock joints have normally been investigated in the past by conducting conventional direct shear test in the laboratory. Direct shear tests using saw tooth profiles have been popularly employed by many researchers (Kodikara et al., 1994; Indraratna, 1998; Homand et al., 2001; Yang et al., 2001; Jafari et al., 2003; Budi et al., 2014), and the influence of infill material on rock joints has been previously introduced by others as well (Amin et al., 2008; Indraratna et al., 2014). However, during the shearing process, the effect of water content of infill material is often neglected.

It is well known that shear strength of rock joints decreases significantly due to the presence of gauge on infill materials (Papaliangas et al.1990; Bertacchi et al.1986; Jahamian et al., 2014). However, only a limited number of studies are found in relation to the influences of infill thickness and water content on the shear strength of infilled joints. In their studies, Indraratna and Haque (1997) found that a very small thickness of bentonite infill reduced the shear strength significantly. The shear strength of joints almost approached that of pure infill, when the ratio t/a of infill thickness t to asperity height a reached 1.6, however, the influence of infill water content on shear strength was not studied by Indraratna and Haque.

The current study by the authors is an attempt to investigate the shear behavior of soft planar and rough joints under constant normal load conditions, with special reference to the influences of infill thickness and water content and shear behavior of planar and rough joints.

2. APPARATUS AND TEST METHOD

The shear box apparatus used in this study was designed and built by GCTS Company (as shown in Photo 1). Specimens of rock of a maximum inner diameter of 152 mm can be tested under normal loads of up to 5 tons and shear loads of up to 10 tons.

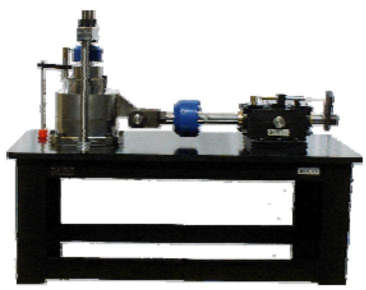


Photo 1 The GCTS shear test machine

The machine consists essentially of an arrangement to accommodate the specimen to be tested, a mechanism to apply different constant vertical loads on the specimen and a mechanism to apply shear loads, in a direction perpendicular to the normal load.

The shear box assembly consists of two different parts, a lower half and a top half. Both halves have the same inner diameter of 152 mm and height of 70.62 mm.

During the test, the vertical and horizontal displacements are measured by 2 LVDT (one vertical and one horizontal). The maximum vertical displacement is 12.7mm, and the maximum shear displacement is 25.4 mm.

Gypsum plaster is used to make ideal soft rock joints, as this material is universally available and is inexpensive. It is easily molded into any shape when mixed with water, and the long term strength does not change significantly once the chemical hydration is completed.

The engineering properties of the model material are determined by conducting tests on specimens cured for two weeks. The cured material has uniaxial compressive strength σ_c of 11.6 MPa and Young's modulus E of 7.9 GPa. Based on rock classification determined by ISRM (1981), model material is a weak rock.

Commercial kaolinite is used as an infill material between the joint interfaces. Atterberg test results show that kaolinite has plastic limit (PL) of 30 and liquid limit (LL) of 50. Direct shear tests indicate that the behavior of this infill material is similar to a compacted earthfill. Therefore, kaolinite is representative of an array of prototype infill materials in relation to shear strength in this study.

After dismantling the top and bottom moulds from the shear apparatus, plaster was mixed with water in the ratio of 2:1 by weight. The bottom mould together with the collar on top was then filled with this mixture, and left undisturbed for one hour to ensure adequate hardening prior to casting the upper specimen. The top of the collar was subsequently shaped according to the predetermined surface profile. Based on Kodikara et al. (1994) suggestion, triangular asperities with asperity height of 6mm and inclination angle of 22.5° were cast for rough joints, as shown in Figure 1. A real specimen before shearing to show the appearance of infill placed on the joint plane is shown in Photo 2. In order to cast fully mated joints, the top mould was placed over the bottom mould and filled with the plaster mixture, and then the whole assembly was air-cured for one hour to complete initial setting. Thin polythene paper was inserted between the two moulds to prevent bonding between the mated joints. During specimen preparation, mild vibration was applied to the mould externally to eliminate any entrapped air. Before testing, the specimens were cured at 30℃ for two weeks and subsequently air cooled to room temperature.

Infill joints were prepared by filling the specially designed collar fitted to the bottom specimen with kaolinite at specific water content, in order to obtain the required thickness.

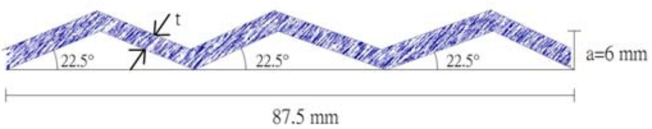


Figure 1 Profiles of saw-tooth plaster joints

(a)

(b)

Photo 2 Real specimen with infill (a)bottom half of specimen with infill (b)upper half of specimen

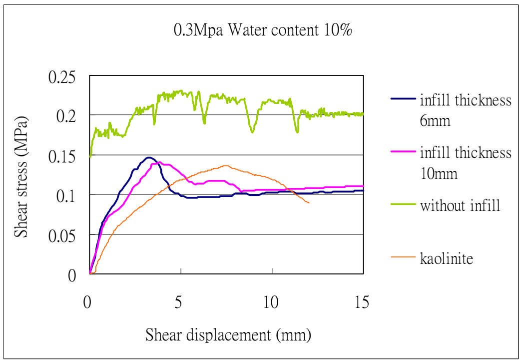
3. TEST RESULTS AND DISCUSSIONS

3.1 Planar joints

Kaolinite is placed in varying thickness (6mm and 10mm) and water content(w=10%, 30%, 35% and 50%) on the bottom half of planar joints, and tested under a normal stress of 0.3 MPa. The variation of shear stress with horizontal displacement for joints with infill thickness of 6mm and 10mm, and infill water contents of 10%, 30%, 35%, and 50%, respectively, are plotted in Figure 2(a) to Figure 2(d). It is observed that if infill water content is less than infill's liquid limit (LL=50), joint with infill thickness of 6 mm has higher peak shear strength and less residual shear strength than that of 10mm. In addition, peak shear strength with infill thickness of 6mm decreases sharply to residual strength, while peak shear strength with infill thickness of 10mm decreases not sharply but slowly to residual strength. When infill water content reaches infill's liquid limit (LL=50), joints with infill thickness of 6mm and 10mm have almost the same shear behavior. Both have nearly the same shear strength without significant peak shear strength, and with smoothly decreasing shear strength.

The variation of shear stress with horizontal displacement for joint without infill is also plotted in Figure 2(a) to Figure 2(d). In their studies, Indraratna and Haque (1997) showed that even a low infill thickness of 1 mm is capable of reducing the peak shear strength of fresh joints by approximately 50%. As the infill thickness is increased further, the peak shear strength is found to decrease, approaching the shear strength of pure infill. Similar results are reported in this study. It is evident from Figure 2 that infill did reduce joint peak shear strength. As the infill thickness increased from 6mm to 10mm, the peak shear strength is found to decrease further. Moreover, the results of this study present the significant effects of infill water content on the joint shear strength. When infill thickness is 10mm, the peak shear strength is approaching infill shear strength. When the infill water content increases to reach its liquid limit (LL), the reduction of joint peak shear strength can be more than that presented by Indraratna and Haque (1997) as shown in Figure 3.

Table 1 summarizes peak shear strength of joints with infill thickness of 6mm and 10mm, and infill water contents of 10%, 30%, 35%, and 50%, respectively. In this study, infill peak shear strength, with various water content, is also presented, as shown is Table 2. Percent of shear strength reduction ratio for infilled joints compared with peak shear strength (0.23 MPa) of fresh joint are also presented in Table 1. As shown is Table 1, reduction ratio of shear strength compared with fresh joint is more than 50% for infill thickness of 6mm and 10 mm, and infill water content of 35%. When infill water content reaches its liquid limit (LL=50), the reduction ratio of peak shear strength is found to be 63% (6mm infill thickness) and 64.7% (10mm infill thickness), respectively.



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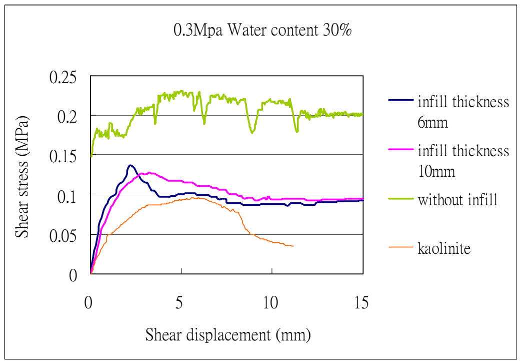

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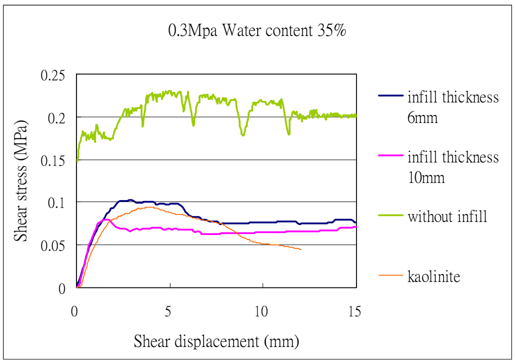

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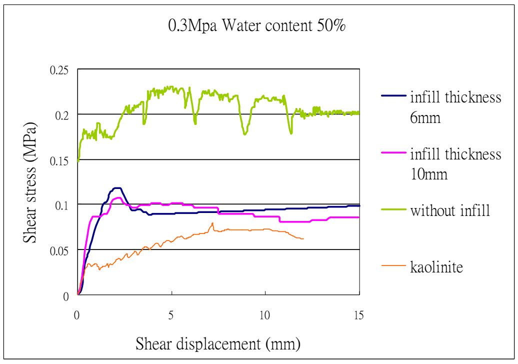


(d)

Figure 2 Shear displacement vs shear stress curves (a) water content 10% (b) water contest 30% (c) water content 35% (d) water content 50%

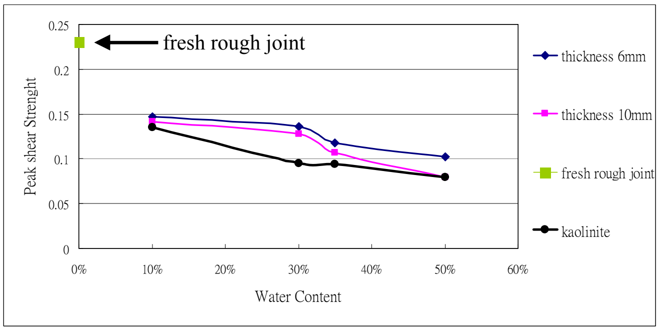


Figure 3 Peak shear strength vs infill water content

Table 1 Joint shear strength for various infill thickness and water content

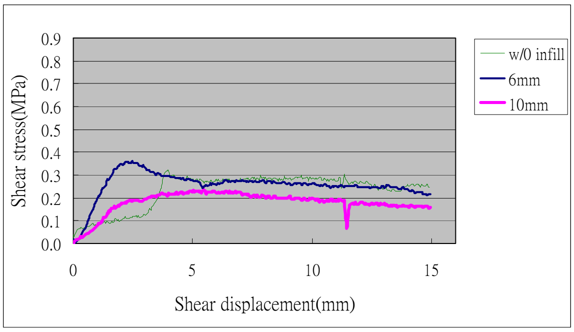
Water content	Infill Thickness		Reduction ratio of shear strength	
	6mm	10mm	6mm	10mm
10%	0.147	0.140	36.0%	39.1%
30%	0.136	0.127	40.8%	44.7%
35%	0.111	0.101	51.7%	56.0%
50%	0.085	0.081	63.0%	64.7%

Table 2 Infill shear strength under 0.3Mpa normal stress

Water content(%)	10	30	35	50
Peak shear strength (Mpa)	0.135	0.095	0.094	0.079

3.2 Rough joints

Kaolinite with two different thickness (t =6mm and 10mm) and varying water content (w=10%, 35% and 50%) is placed on the bottom half of rough joints, and tested under various normal stresses of 0.3MPa, 0.5MPa and 1.0MPa. The variation of shear stress with horizontal displacement for joints with infill thickness of 6mm and 10mm, and infill water contents of 10%, 35% and 50%, under tested normal stresses of 0.3MPa, 0.5MPa and 1.0MPa, are plotted in Figure 4 to Figure 6. Test results for peak shear strengths under various conditions are summarized in Table 3.



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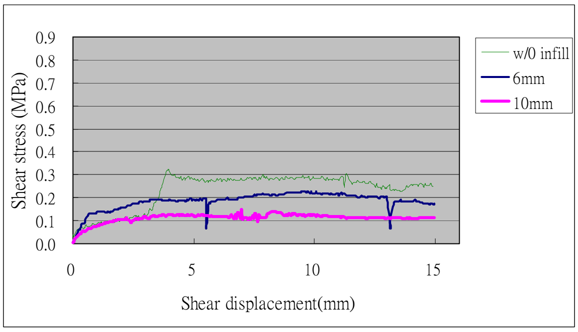

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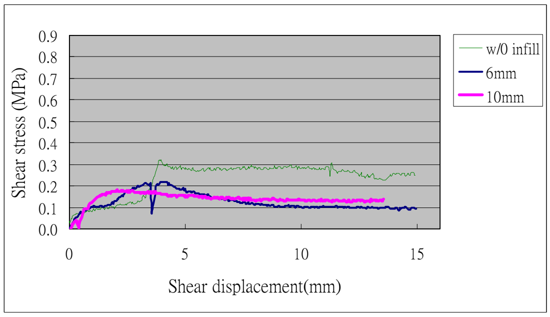
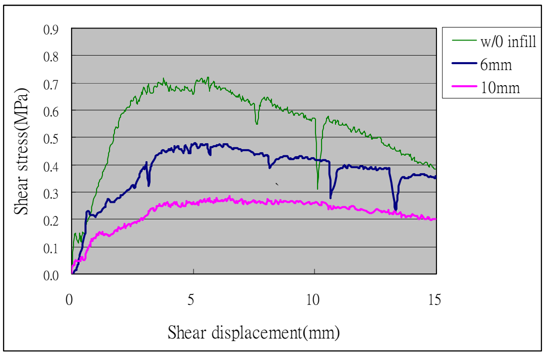


(c)

Figure 4 Variation of shear stress with shear displacement under 0.3MPa normal stress (a) 10% infill water content, (b) 35% infill water content, (c) 50% infill water content

From Figures 4-6 and Table 3, it is observed that except for Figure 4a, infill water content, as well as thickness, can reduce peak shear strength of rough joints significantly. Under lower normal stress of 0.3MPa with infill water content of 10%, peak shear strength of rock joint is a little higher than that without infill. With 6mm infill thickness, as the joint was sheared under lower normal stress of 0.3MPa, one asperity is easily to ride over another. Joint is sheared under peak-to-peak condition, results in higher peak shear strength than that without infill. Figure 7 shows variation of peak shear strength with infill water content for joints with infill thickness of 6mm and 10mm under normal stresses of 0.3MPa, 0.5MPa and 1.0MPa. As shown in Figure 7(a), peak shear strength of joints decreases as infill water content increases. Under lower normal stress of 0.3MPa, the peak shear strength is found to decrease more, As infill water content increases from 10% to 50%, peak shear strength decreases from 0.36MPa to 0.22MPa. Jafari et al.(2003) showed that at low levels of normal stress, the main shearing mechanism is sliding along the asperities. The sample continues to slide until it slides over asperity. However, at intermediate level of normal stress (0.5MPa), shear strength does not decrease but increases as water content increases from 35% to 50%. As shown in Table 3 or Figure 4, shear displacement required to reach peak strength sharply decreases from 5.59mm (w=10%) and 3.98mm (w=35%) to 2.12mm (w=50%). As infill water content reaches its liquid limit of 50, sample slides along the asperity easilier and more quicklier (Photo 3(a)) and the tooth is broken soon once the sample tries to slide over the asperity when joint is sheared at high levels of normal stress 1.0MPa (Photo 3(b)). At high normal stress, contraction of asperity plays an important role in the mechanism of shearing.



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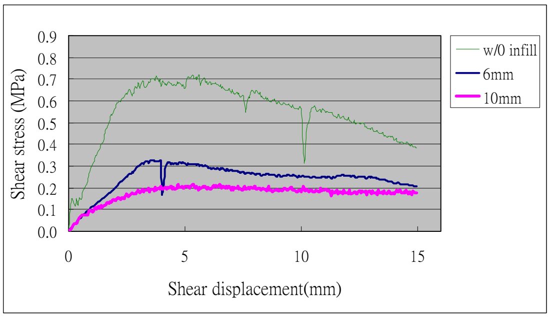

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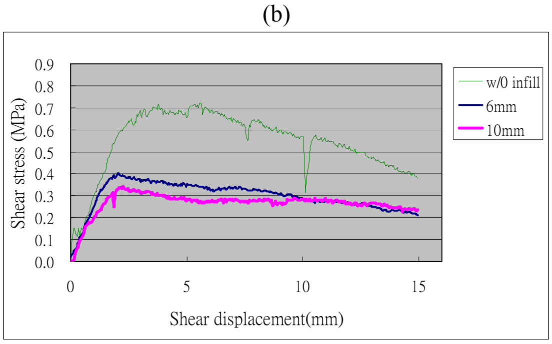
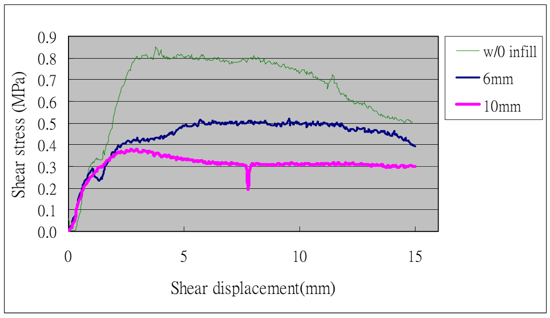


(c)

Figure 5 Variation of shear stress with shear displacement under 0.5MPa normal stress (a) 10% infill water content, (b) 35% infill water content, (c) 50% infill water content

For joint with infill thickness of 10mm (Figure 7(b)), shear behavior are almost the same as that of 6mm, except that shear strengths for joints with 10mm infill thickness are less than that of 6mm. In their studies of joint asperity degradation during cyclic shear, Hutson and Dowding (1990) showed that for very low normal stress/unconfined compressive strength (N/q_u) ratios, little or no asperity degradation during the first cycle will be induced, however, for larger N/q_u ratios, significant asperity degradation will be produced. Hutson and Dowdings' findings may confirm the above mentioned results.



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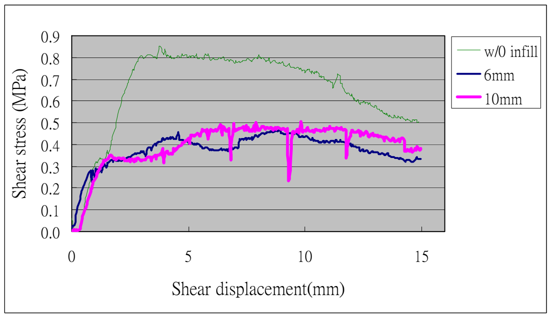

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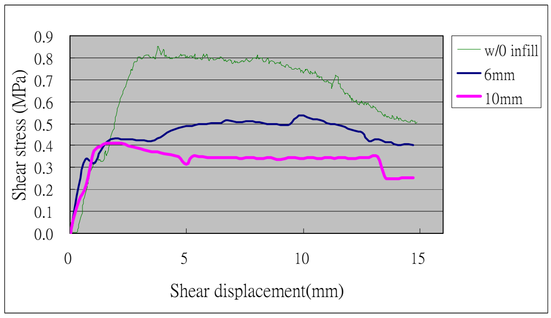

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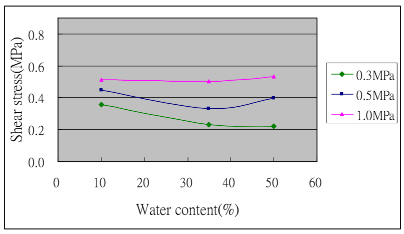
Figure 6 Variation of shear stress with shear displacement under 1.0MPa normal stress (a) 10% infill water content, (b) 35% infill water content, (c) 50% infill water content



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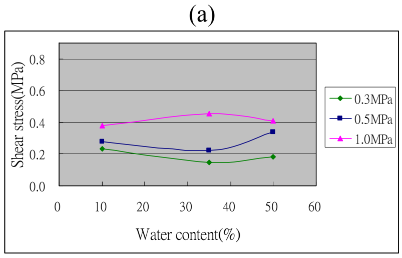

(b)

Figure 7 Variation of shear stress with infill water content (a) 6mm infill thickness, (b) 10mm infill thickness

(a) (b)

Photo 3 Failure pattern after joints are sheared with t/a=1 and w=50% (a) σ_n =0.3MPa, (b) σ_n =1.0MPa

To quatitatively investigate the effect of infill thickness on shear behavior of rock joints, the same interface profile was used with infill 35% water content but different infill thickness, and tested under 1.0MPa normal stress. Table 4 summarizes test results. Reduction ratios of peak shear strength for infilled joints with different infill thickness compared with peak shear strength of fresh joint are also presented in Table 4. As shown in Table 4, it is observed that a low infill thickness of 1.5mm is capable of reducing the peak shear strength of fresh joints by approximately 37%. As the infill thickness increases further, the peak shear strength is found to decrease more. The shear strength of rough joint decreased almost 50% when the infill thickness to asperity height ratio is 1.66 (t/a=10mm/6mm).

Table 3 Joint peak shear strength and displacement with different infill thickness and water content under various normal stresses.

water content (%)	10%						35%						50%					
normal stress (MPa)	0.3		0.5		1.0		0.3		0.5		1.0		0.3		0.5		1.0	
infill thickness (mm)	6	10	6	10	6	10	6	10	6	10	6	10	6	10	6	10	6	10
peak shear strength (MPa)	0.36	0.23	0.45	0.28	0.51	0.38	0.23	0.15	0.33	0.22	0.50	0.45	0.22	0.18	0.40	0.34	0.53	0.41
shear displacement (mm)	2.63	5.12	5.59	5.98	5.72	2.92	9.74	6.79	3.98	4.71	9.81	8.82	4.22	2.07	2.12	2.27	9.82	1.94

Table 4 Peak shear strength of infilled joints with 35% water content and various infill thickness under 1.0MPa normal stress

infill thickness(mm)	0	1.5	3.0	6.0	8.0	10
t/a	0	0.25	0.5	1.0	1.33	1.66
peak shear strength (MPa)	0.85	0.54	0.51	0.50	0.46	0.45
reduction ratio (%)	0	37	40	41	46	48

The joint shear strength did not approach that of pure infill (as shown in Table 5), when the infill thickness to asperity ratio reached 1.66, as presented by Indraratna and Haque (1997). It is believed that is due to the effect of asperity angle and asperity height. In their studies, where samples with 11 to 13MPa uniaxial compressive strength tested under normal stresses ranging from 0.05 to 2.43MPa, Indraratna and Haque found that the peak shear stress was measured to be significantly higher if the angle of asperity is greater. The asperity angle (22.5°) used in this study is much greater than that of Indraratna and Haque (9.5°). In addition, the asperity height (6mm) used in this study is also bigger than that of Indaratna and Haque (2.5mm). Furthermore, the infill material (bentonite) in Indaratna and Haque studies may be another reason why joint shear strength is easy to approach that of infill. If the peak shear strength wants to be equal to that of the pure infill, t/a ratio should be higher, if asperity height and inclination angle are bigger.

Table 5 Peak shear strength of infilled joints

Water content / Normal stress	**10%**	**35%**	**50%**
0.3 MPa	—	—	—
0.5 MPa	—	0.136	0.124
1.0 MPa	—	0.246	0.213

4. CONCLUSION

Test results of this investigation show that shear strength of infilled joints diminishes with the increased infill water content, as well as increased infill thickness. The variation of peak shear strength of planar joint shows that for infill water content of 35%, the peak shear strength for both infill thickness of 6mm and 10mm decreases more than 50%, and decreases by 63% (6mm) and 64.7% (10mm) for infill water content approaching its liquid limit of 50.

Infill water content also decreases shear strength of rough joints, as significantly as infill thickness, if infill water content does not reach its liquid limit (LL). As water content of infill reaches its liquid limit, sliding along asperities may occur easier and quicker. However, saw tooth is harder to break under higher normal stress (0.5 and 1.0MPa), makes shear strength with infill water content of 50% be higher than that of 35%.

The variation of rough joint peak shear strength with infill thickness/asperity height (t/a) ratio confirms that for a t/a ratio of 0.5, the peak shear strength may decrease by more than 40%. Due to high inclination angle and asperity, shear strength does close to but not reach that of pure infill for t/a ratio approaching 1.6, as presented by Indraratna and

Consequently, infill asperities with bigger inclination angle, failure is not easy to occur as we expected, if rough joints were loaded under high normal stresses, even infill water content is high.

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