Characteristics of filled joint under shear loading

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Abstract— Filled joints, particularly those resulting from *in situ* deposition, are among the most critical discontinuities in rock. High deformability and low shear strength are the typical behaviour exhibited by this type of discontinuity. There are certain components or features that contribute to the weaknesses exhibited by filled joint, and these include type and thickness of infilling, and surface roughness of the host joint. Due to the complex behaviour of filled joint, it is therefore essential to at least understand its typical behaviour under the interactive effects of these controlling components. In an attempt to study the behaviour of filled joint, a series of laboratory shear tests were undertaken on model filled joint. The physical model used in the test consists of granite residual soils as infilling and cast concrete blocks as joint blocks. Experimental variables include normal stress, infill thickness and roughness of joint surface. The shear tests were undertaken on specially fabricated servo-controlled direct shear apparatus. Laboratory test results indicate that shear strength of a joint decreases significantly with the presence of infill material in its aperture. The reduction in strength however, depends on the infill thickness and texture of the joint surface. Comparatively, the effect of infill thickness on shear strength is more significant in rougher joint surface. It is also found that the weakest point in joint filled with granular material is not necessarily within the infill, but may occur at the 'infill-joint interface'.

Keywords: filled joint, granular infill, infill thickness, joint surface, shear loading

INTRODUCTION

Filled joint can be classified according to the origin of its infilling (Chernyshev *et al*., 1991) and these include; (a) minerals deposits caused by hydrothermal solutions; (b) products of differential weathering host rock, and (c) in-washed surface sediments.

Based on its nature, joint with weaker infill is known to exhibits lower strength and higher deformability (Mohd Amin & Kassim, 1999). This study focuses on filled joint classified as type (c) above. This particular joint is usually associated with jointed rock body located at shallow depth or exposed on the surface. In granite rock mass, the infill is commonly consists of granular residual soil. With regard to construction activities (e.g. slope excavation), these joints will require immediate attention. Their behaviour, particularly under shear loading, is essential in anticipating any immediate problems on excavation of a rock mass that exhibits these filled joints.

LITERATURE REVIEW

The behaviour of granular material, when acting as an infill alone, is affected by its texture (e.g. size, shape, strength and grading of its particles). Similarly, when joint is filled with a granular material, its behaviour is affected to a certain degree, by the texture of its infilling (De Toledo & De Freitas, 1993; Mohd Amin *et al*., 2007). The strength of a joint filled with thick granular material, generally corresponds to the relative amount of massive and coarser minerals in the infill. The importance of the properties of the material constituents of the infill is relevant when failure mechanism of the filled joint is controlled by the infill and with minimal interaction of the joint walls. A number of findings from previous work on joint filled with fine-grained granular material are outlined below:

For a rough joint with granular infill, the shear strength reduction is less rapid with increasing infill thickness, compared to finer grains infill (Papaliangas *et al*., 1993; De Toledo & De Freitas, 1995).

The peak strength of rough joint with granular infilling decreases and becomes less defined with increasing infill thickness (Phien-wej *et al*., 1991). For a smoother joint surface, no peak strength (strain hardening) is observed for all infill thickness (Pereira, 1990).

For a given joint roughness, the shear strength of filled joint increases with increasing proportion of coarse and angular grains in the infill (Pereira, 1990).

It can be inferred that shear behaviour of a joint with granular infill is not only affected by the texture of the infill but also by the roughness of the joint surface. A gradual reduction in shear strength with increasing infill thickness reflects a gradual reduction in the frictional resistance of the infill due to less constraint imposed by the joint surface. Lack of peak shear strength verifies the storage of elastic energy in the shear direction, as long as frictional contact existed between particles and between infill and joint wall. This also indicates the co-existing of failure within the infill and at the infill-joint interfaces.

The thickness of infill in joint varies from a few millimetres to several metres. The degree of roughness of joint surface depends on scale being considered and rock type. Typically, for tension joint it is characterised by wavy to planar profile with small scale roughness (asperities) (Bandis, 1993; Barton & Choubey, 1977).

For granular infill, the effect of thickness on shear strength of joints depends on the roughness amplitude (a) of the joint surface. For a given (a) the strength seems to approach that of the infill with increasing infill thickness (t). For a relatively thin infill (t < a), the joint walls set the boundary limits for the failure surface and therefore, the texture of the joint walls controls the failure. Due to the inhomogeneous nature of the infill and the interactive effect of the joint wall, it is often observed that when the difference between (t) and (a) approaches zero, the strength of the joint tends to increase above that of the infill. When t > a, the joint can fail along a continuous surface without any interaction of the joint wall hence, the strength approaches that of the infill (De Toledo and De Feitas, 1993).

When joint is filled with granular (frictional) material, there is a tendency for failure to occur at planes of lowest resistance. This was verified by Pereira (1990) and Papaliangas *et al*. (1993) where, failure tends to occur at the interface between the infill and the joint wall, and usually resulting in joint strength lower than the infill alone. This phenomenon is due to the difference in surface roughness between infill and joint wall as shown in Figure 1. The influence of the joint surface may be felt when its surface roughness is smoother than the roughness of the infill surface (particle size distribution of granular material). When joint surface is rough enough to prevent particles movement then, sliding friction in the infill has to be overcome for failure to occur. Planar joint surface facilitates grains rearrangement by rotation then, only rolling friction has to be overcome.

LABORATORY TEST

Series of laboratory shear tests on model filled and unfilled joints were carried out. The models were prepared based on the typical characteristics of filled joint observed at the study site in Lahat, Ipoh. The related field assessments and index tests carried out in characterising the filled joint are discussed in Mohd Amin *et al*., (2007).

Shear test equipment

There are several fundamental aspects that need to be considered when assessing behaviour of joints under shear loading:

a) Dilation of unfilled joint due to its surface roughness, and compression of filled joint due to the compressibility its weak infilling.
b) Scale effect due to size of sample relative to the roughness amplitude of joint surface and grain size of infill.

Shearing of rough joint is normally associated with dilation and compression, and this may lead to the variations of applied normal load and shearing rate, as schematically explained in Figure 2. Shearing of joint with thick infill is usually compressive in nature and consequently, reduction in normal load is inevitable. In addition, the consistency of joint behaviour can only be assured if the ratio between the size of the joint sample and its maximum roughness amplitude (for unfilled joint), and maximum grain size of infill (for filled joint) are about 15 to 20 (Ong Heng Yau, 2006). Therefore, all the shear tests were undertaken on servo-controlled direct shear apparatus (see Figure 3), which provides the essential requirements for the shear tests:

Closed-circuit servo-control system in the loading mechanisms ensures correct simulation of shear loading modes (constant normal load and shearing rate).

Rigid loading frames (hardened steel) to absorb any build-up of strain in the frame, and this would give a more gradual shearing behaviour.

The scale effect due to joint roughness and grain size of infill is reduced by using a larger shear-box of 300 mm square cross-section.

Physical model for clean and filled joint

Infill material was acquired from the exposed filled joints at the study site. The infill is essentially a granite residual soil, and sieve tests indicate that it is a well-graded silty-SAND. More than 60 % of the infill consists of fine to coarse sand which implies that it is a granular (frictional) material. Variations in shear strength (mainly frictional) are likely, and this is due to the varying particle sizes.

Grade 60 cast concrete blocks (equivalent to rock of 60 MPa UCS) were used as joint blocks. In this paper only two types of surface textures for the joint blocks are discussed, and these are planar surface representing smooth joint (Joint Roughness Coefficient, JRC value 0 to 4), and saw-toothed surface representing rough joint (JRC 16 to 20). The cast blocks are shown in Figure 4. The profile for the saw-tooth consisted of 5 mm peak height (amplitude) and 15 mm distance between each peak.

Test program

The various shear tests conducted is summarised in Table 1, which consists of shear test on the infill material, unfilled (clean) joint and filled joint with various infill thickness. The normal stresses applied during shear were A (133 kPa), B (264 kPa) and C (396 kPa). The typical test setup is shown in Figure 5 and Figure 6.

DISCUSSION OF TEST RESULTS

More than 30 number of shear tests were conducted on different joint models however, only those shear tests conducted at the highest normal stress (C = 396 kPa) will be discussed. The shear stress-displacement curves at normal stress C, for smooth clean (unfilled) joint and smooth filled joint, are shown in Figure 7. For comparison purposes, the plot for the infill material alone is also included. The shear stress-displacement curves at normal stress (C), for rough clean (unfilled) joint and rough filled joint, are shown in Figure 8, inclusive of the plot for the infill material alone.

Shear strength of infill alone

Result from shear tests at normal stress C on the infill material alone is shown as ‘IC’ in Figures 7 and 8. Under

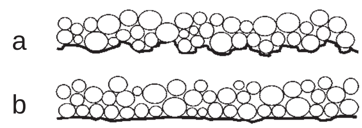

Figure 1: Boundary effect of (a) infill-rough joint and (b) infill-smooth joint.

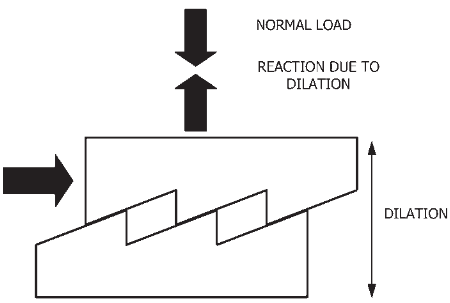

Figure 2: Fluctuations of normal stress due to dilation.

Figure 3: Servo-controlled direct shear test equipment.

shear loading, the infill material exhibits strain-hardening behaviour (similar behaviour at other normal stresses (A & B)). The shear strengths however, remain constant when sheared beyond 20 mm displacement.

Shear test on unfilled joint

To evaluate the shear strength of unfilled joint, direct shear tests were carried out on smooth and rough joint models. The resulting shear strength at normal stress C for smooth unfilled joint is denoted as 'SUC' in Figure 7, and for rough unfilled joint as 'RUC' in Figure 8.

The peak strength for smooth unfilled joint was mobilised immediately upon shearing and tend to increase with normal stress. These peak strengths represent the shearing off of the surface asperities (small-scale roughness). The rough joint exhibits sinusoidal-shaped curve, a shape

Table 1: Shear test program. Normal stress A = 133 kPa, B = 264 kPa and C = 396 kPa.

Type of shear test	Joint condition	Normal stress	Infill thickness (t)
Infill alone (I)	Not applicable	A, B, **C**	t = 30 mm
Unfilled or clean joint:			
-Smooth unfilled (SU)	Smooth (planar)	A, B, **C**	Not applicable
-Rough unfilled (RU)	Rough (saw-tooth)	A, B, **C**	
Filled joint:			
-Smooth filled (SF)	Smooth (planar)	A, B, **C**	1. t=5 mm 2. t=10 mm 3. t=15 mm 4. t=single grain size
-Rough filled (RF)	Rough (saw-tooth)	A, B, **C**	1. t=5 mm 2. t=10 mm 3. t=15 mm

Figure 4: Cast joint blocks; smooth (planar) and saw-toothed (rough) surface.

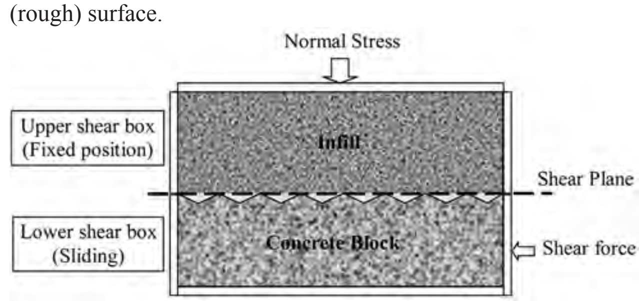

Figure 5: Test setup for direct shearing of the infill on rough joint surface.

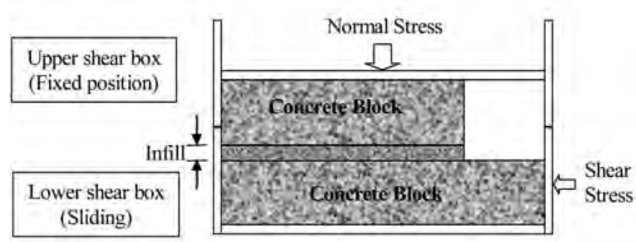

Figure 6: Test setup for shear test on filled joint (sandwich shear test).

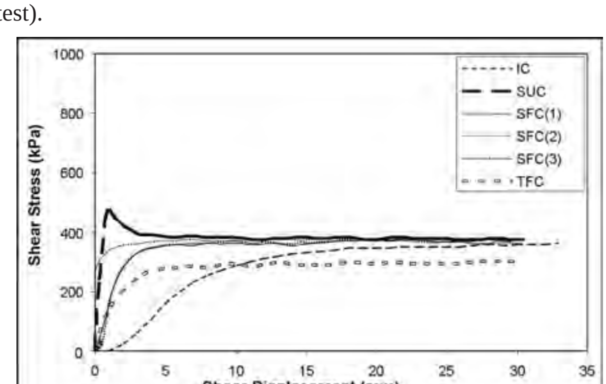

Figure 7: Shear stress-displacement curves for smooth joint (clean and filled), under normal stress C = 396 kPa.

which is similar to the saw-tooth profile of the sample. This implies that during shear, the peaks of the interfacing joints simply glided passing each other, instead of being sheared off. Full contact between the interfacing joints occurs when they interlocked (matched) with each other. In this condition, a higher shear stress is required for further shearing as it is associated with the sliding up of the saw-tooth. However, when the joint begins to dilate, the contact area between joint walls starts to decrease (contact at peaks only) and this reduces the shear resistance. The lowest shear strength occurs shortly after the corresponding peaks slide over each other.

Shear strength of smooth filled joint

The shear tests at normal stress C on smooth filled joint (SFC) were undertaken with infill thickness t = 5mm (1), 10mm (2) and 15 mm (3). In Figure 7, the typical shear stress-displacement curves for these tests are labeled as SFC(1), SFC(2) and SFC(3). There is no visible influence of the infill thickness on the shear strength, even at other normal stresses (A and B). The strength increases abruptly within the first 5 mm displacement and remains constant thereafter. No clear peak strength is visible and therefore, in contrast to clean joint, this joint does not display any peak strength throughout the shearing process. The vertical displacement during shear is mainly compressive (the plot is not shown here) and exhibits two distinctive stages. Within the first few millimeters of shear, the initially loose infill compresses upon the application of the normal and shear stresses. The amount of settlement during this stage is proportional to the normal stress and the initial infill thickness. As rearrangement of the infill particles takes place, voids are eventually reduced. This reduces the available spaces for further rearrangement of the particles and therefore, the subsequent contraction of the filled joint occurs at a slower rate.

The curve denoted as ‘TFC’ in Figure 7 represents the result of shear test on smooth joint with a very thin infill (equivalent to single grain size of about 2 mm). The shape of the curve is similar to that of the smooth filled joint (SFC curves). Rapid increase in shear stress occurred within the first 5 millimeters and the rate gradually reduced with subsequent shearing. With very thin layer of infill in between the smooth joint, the shearing is controlled by rolling and rotating of the infill particles. Rolling of the sub-angular particles produces fluctuation of frictional resistance and this leads to the irregularities in the shear stress-displacement curve.

Shear test on rough filled joint

Figure 8 exhibits the shear stress-displacement curve for rough filled joint at normal stress C (denoted as ‘RFC’) and infill thickness 5 mm (1), 10 mm (2) and 15 mm (3). Almost similar shear behaviour is observed at other normal stresses. The figure verifies the influence of joint roughness and infill thickness on the shear characteristics of this joint. A sinusoidal curve of distinctive peaks and troughs is displayed by the 5 mm infill (RFC(1)) and this an indication on the influence of the joint surface profile on the behaviour of filled joint, particularly with thinner infill. The effect of joint roughness decreases with thicker infill, for the infill material creates a cushioning effect during overriding of saw-tooth peaks of the joint. When the thickness of the infill exceeds the height of the peaks, the irregular compression of the infill caused by the undulating joint surface, is being over-shadowed by the gross settlement due to the particle rearrangement of the infill. Therefore, the shear stress-displacement curves for rough joint with thicker infill (RFC(2) and RFC(3)) are smoother and more gradual. Based on the shear tests at other normal stresses (A and B) it can be inferred that higher shear strength is observed in joint with thinner infill. However, there were instances (throughout the shearing) where the shear strength of the thin filled joint (RFC(1)) is even lower than that of the thicker infill (RFC(2) and RFC(3)). This can be attributed to the sliding down of the saw-toothed surface, and this signifies the importance of surface texture in rough joint with thin infill.

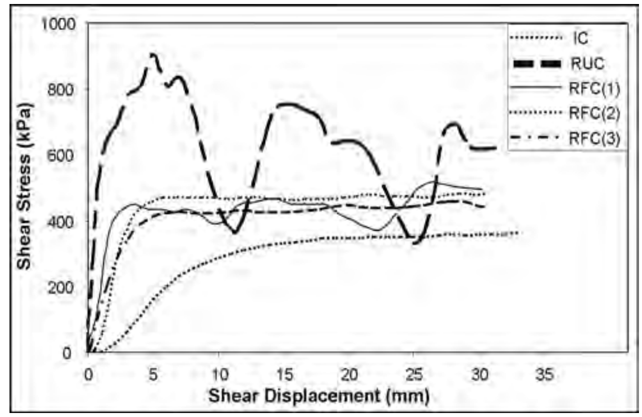

Figure 8: Shear stress-displacement curves for rough joint (clean and filled), under normal stress C = 396 kPa.

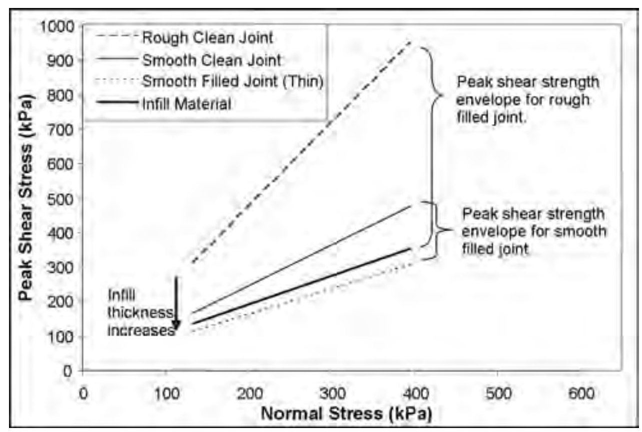

Figure 9: Peak shear strength envelope of various types of joint.

DISCUSSION AND CONCLUSION

The effects of infill material on the behaviour of smooth and rough joints have been discussed. Clean smooth joint attains its peak shear strength almost immediately upon shearing and followed by strain-hardening behaviour with no visible peak strength. Infill thickness has no significant effect on the behaviour of smooth joint. Not much variation in term of residual strength for clean joint, filled joint and infill material, with the shear strength of filled joint lies in between the shear strength of clean joint (upper limit) and infill material (lower limit). Nevertheless, exceptionally low shear strength is observed for smooth joint with very thin infill, and this has been ascribed to the boundary effect. The presence of infill in the rough joint aperture leads to significant reduction in its shear strength. The peak shear strength of rough clean joint was reduced as much as 50 % with the presence of merely 5 mm infill. Rough joint with thicker infill does not exhibit clear peak strength compared to unfilled joint. Despite of the thick infill, the shear strength of the rough filled joint is still higher than that of the infill (about 30 % higher), and this is due to the interaction of the rough joint walls.

The shear strength envelope for the various types of joint modeled in this study is proposed as Figure 9. The upper limit of the strength envelope is expected to increase with increasing degree of roughness (JRC) of joint surface. The shear strength of smooth joint with very thin infill forms the lowest limit of the strength envelope.

Finally the following conclusions can be derived from the laboratory study:

1) Shear behaviour and strength of filled joint is influenced by roughness of joint surface, type and thickness of infill. Under shear loading the behaviour of filled joint is also affected by the level of applied normal stress.
2) The effect of granular infill on smooth joint becomes more significant when infill occurs in a very thin layer. Such thin infill may induce shear strength that is lower than the strength of the infill alone and this occurs at the joint-infill boundary.
3) For filled joint with rough surface, infill thickness controls its shear strength. With increasing infill thickness, the interaction of the rough joint surface starts to decrease consequently, the shear strength of the joint approaches that of the infill.

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REFERENCES

Bandis, S.C., 1993. Engineering properties and characterisation of rock discontinuities, In: Hudson, J.A., Brown, E.T., Fairhurst, C. & Hoek, E. (eds.), Comprehensive Rock Engineering: Principles, Practice and Projects, V. 1 1st. edition, Pergamon Press, pp. 155-183.

Barton, N. & Choubey, V., 1977. The Shear Strength of Rock Joints in Theory and Practice. Rock Mechanics. Vol. 10, 1-54.

Chernyshev, S. N. , Dearman, W. R. & Mirovsky, G.B., 1991. Rock Fractures. 1st. ed., Butterworth-Heinemann Ltd., 272 p.

De Toledo, P. E. C. & De Freitas, M. H., 1993. Laboratory testing and parameters controlling the shear strength of filled rock joints. Geotechnique. 43, 1, 1-19.

De Toledo, P. E. C. & De Freitas, M. H., 1995. The peak shear strength of filled joints. Proceedings of International Symposium on Fractured and Jointed Rock Masses. Balkema, preprint V.2, 358-365.

Mohd Amin, M. F. & Kassim, A.,1999. Mechanics of rock joint filled with weak, granular material. Civil and Environmental Enginnering Conference, New Frontiers and Challenges. Bangkok, Thailand, VII-53 – VII-62.

Mohd Amin, M.F., Mohammad, E.T., Kassim, A. & Ong, H.Y., 2007. Classification of filled joint based on the characteristics of its constitutive components, Research Report Vot 71825, Research Management Centre, Universiti Teknologi Malaysia, Johor, 103 p.

Ong Heng Yau, 2006. Behaviour of filled joint under shear loading, Unpublished Master of Engineering (Geotechnics) Thesis, Universiti Teknologi Malaysia, Johor, 207 p.

Papaliangas, T., Hencher, S. R., Lumsden, A. C. and Manolopoulou, S., 1993. The effect of frictional fill thickness on the shear strength of rock discontinuities. International Journal of Rock Mechanics and Mining Sciences & Geomechanical Abstracts. 30(2), 81-91.

Pereira, J. P., 1990. Mechanics of filled discontinuities. Proceedings of International Conference on Mechanics of Jointed and Faulted Rock, Vienna, pp. 375-380.

Phien-wej, N., Shrestha, U. B. & Ching-Yuan, H., 1991. Strength and displacements of model infilled rock joints. Proceedings Developments in Geotechnical Aspects of Embankments, Excavations and Buried Structures, Thailand, pp. 123-132.

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