2019

Shear strength of rock joints under constant normal loading conditions

Ali Mirzaghorbanali
University of Southern Queensland, University of Wollongong

Faisel Alenzel
University of Southern Queensland

Peter Gregor
University of Southern Queensland

Naj Aziz
University of Southern Queensland, University of Wollongong, naj@uow.edu.au

Kevin McDougall
University of Southern Queensland

See next page for additional authors

Recommended Citation

Ali Mirzaghorbanali, Faisel Alenzel, Peter Gregor, Naj Aziz, Kevin McDougall, and Andreas Helwig, Shear strength of rock joints under constant normal loading conditions, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2019 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019
https://ro.uow.edu.au/coal/736

Authors
Ali Mirzaghorbanali, Faisel Alenzel, Peter Gregor, Naj Aziz, Kevin McDougall, and Andreas Helwig

SHEAR STRENGTH OF ROCK JOINTS UNDER CONSTANT NORMAL LOADING CONDITIONS

Ali Mirzaghorbanali[1,2], Faisel Alenezi[1], Peter Gregor[1], Naj Aziz[1,2], Kevin McDougall[1] and Andreas Helwig[1]

ABSTRACT: The variation of shear strength of rock joints under constant normal loading conditions was studied. Three dimensional printing technology was incorporated to produce moulds of rock joints. Rock joints samples with three different roughness values were cast using concrete with uniaxial compressive strength of 20 MPa. Samples were sheared using a direct shear testing machine for normal stress values ranging from 0.25 to 0.7 MPa. In addition, effects of shear rate on shear strength properties of rock joints were experimentally investigated. It was found that the shear strength of rock joints is a function of normal stress, joint roughness and shear rate values. In addition, it was shown that three dimensional printing technology is a useful tool to replicate real rock joints.

INTRODUCTION

Joints in a rock mass have a significant effect on the shear strength and deformation properties of the rock. Lama (1978) investigated the mechanical behaviour of a rock mass and indicated that for closely spaced joints, the mechanical performance of the rock mass is similar to the mechanical behaviour of the joints. In the past, several researchers carried out tests to explore shear behaviour of rock joints. Patton (1966), Ladanyi and Archambault (1969), Barton (1973, 1976 and 1986), Hoek (1977, 1983 and 1990), Hoek and Brown (1985), Bandos *et al*., (1981), Hencher (1989), Kulatilake (1993) and Saeb and Amadei (1992) performed research investigations on shear strength properties of both artificial and natural unfilled rock joints under Constant Normal Load (CNL) condition where dilation is not restricted during shearing.

Real rock joints have three dimensional roughness distributions which cannot be accurately simulated by artificial triangular or sinusoidal rock joints. In this context, Mirzaghorbanali *et al.,* (2014) suggested that research studies on shear behaviour of rock joints should be carried out on real rock joints. Nevertheless, real rock joints with the same surface roughness value are rarely to be found in nature, thus, experiments repeatability is a challenge for researchers.

This paper describes experimental investigations into shear strength properties of joints cast using moulds of real rock joints for various normal stress and shear rate values under CNL conditions. Three dimensional printing technologies were incorporated to prepare moulds of real rock joints, facilitating shear test repeatability.

SAMPLE PREPARATION

Three moulds with different roughness values were prepared for this experiment. They were named as: 1R, 2R and 3R. As shown in Figure 1, moulds were made in pair using a blue material, incorporating three dimensional printing technologies as per direct shear testing machine specifications. Subsequently, a concrete mixture was produced and added inside the PVC moulds as shown in Figure 2(a). Once samples dried, they were taken out from moulds and left undisturbed for 28 days. Cylindrical samples were prepared using the same mixture for Uniaxial Compressive Strength (UCS) determination. USC was found to be 20 MPa after 28

---

[1] *School of Civil Engineering and Surveying, University of Southern Queensland, QLD, 4350, Australia.*
[2] *School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW, 2500, Australia.*
Corresponding authors' email and phone: ali.mirzaghorbanali@usq.edu.au, T: +61 7 6431 2919

days. Figure 2(b) shows one of the prepared samples. All samples had the same cross sectional diameter of 63.4 mm. This diameter was used to calculate the cross sectional area of the samples and for the shear and normal stress calculations. At the final stages, the pair of samples were positioned on each other to be placed in the shear testing machine which exerted different normal loads of 750 N, 1250 N, 1750 N and 2200 N.

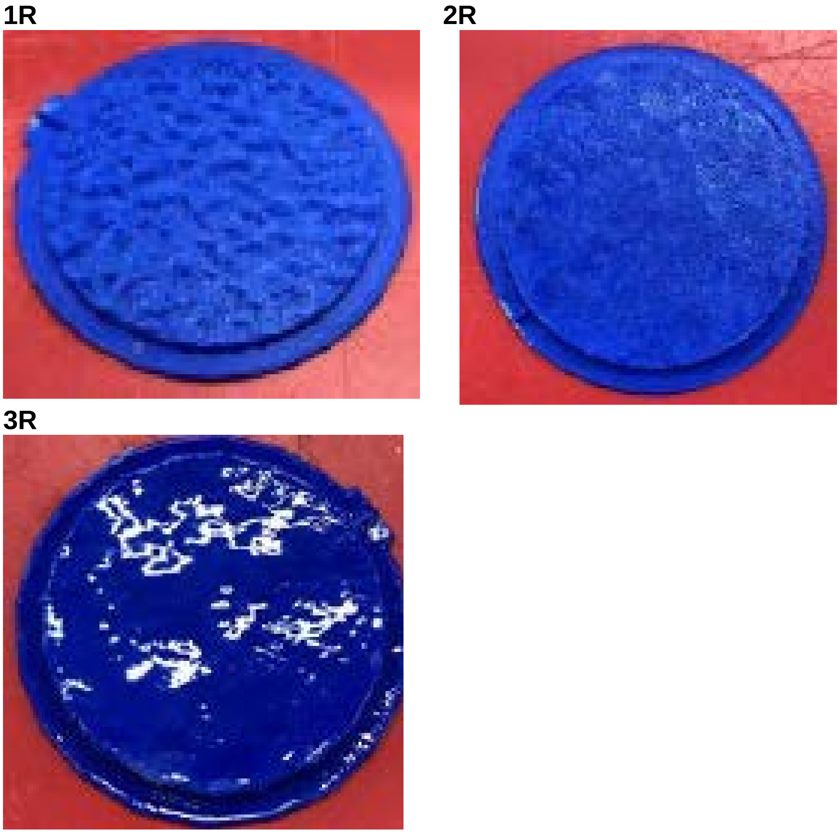


Figure 1: Moulds of rock joints prepared using three dimensional printing technology

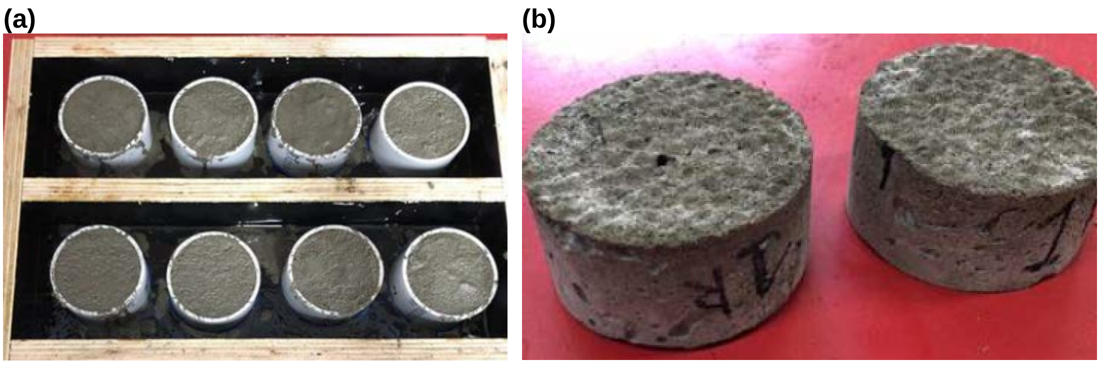


Figure 2: (a) Sample preparation procedure (b) prepared sample based on R1 mould

TESTING PROCEDURE

The testing machine which was used to apply the shear and normal load on the samples is ShearTrac ii as shown in Figure 3. This is an automatic loading system which includes transducers. The amount of load which this machine applies on the testing samples is controlled based on the feedback from these transducers. This machine is equipped with the sensors of two force transducers (normal and shear) and two transducers for horizontal and vertical displacement.

Figure 3: Fully automated direct shear testing machine

The system is connected to a computer to monitor the amount of load which is exerted to the samples. The computer loads or unloads the loading frame until the amount of loading which is read by the transducers becomes equal to the values required for testing the samples. Two-step motors connected to the gearing systems provide the normal and shear loads. They enable the loading mechanism to be raised and lowered for exerting the normal load and to be moved left and right for applying the shear load.

Each pair of samples was held together and mounted on the shear box in the testing machine. After calibrating the vertical and horizontal position of the sample with the normal and shear loading arms, the vertical load was set to a fixed value since the test was performed under constant normal load of 750 N, 1250 N, 1750 N and 2200 N. In the next step, the shear or horizontal load was applied and increased until the upper part of the sample slid over its lower part. It should be mentioned that the shear load was applied at a rate of 2 mm per minute for part (A) of the testing campaign.

The values of both normal and shear load and dilation results were displayed on the computer monitor during the test. This procedure was repeated for all samples under the specified loads. Shear and normal displacements were measured by the transducers and the experimental data was saved on the computer. Figure 4 indicates samples 2R when it is under a constant normal loading of 1250 N within the testing machine.

a) b)

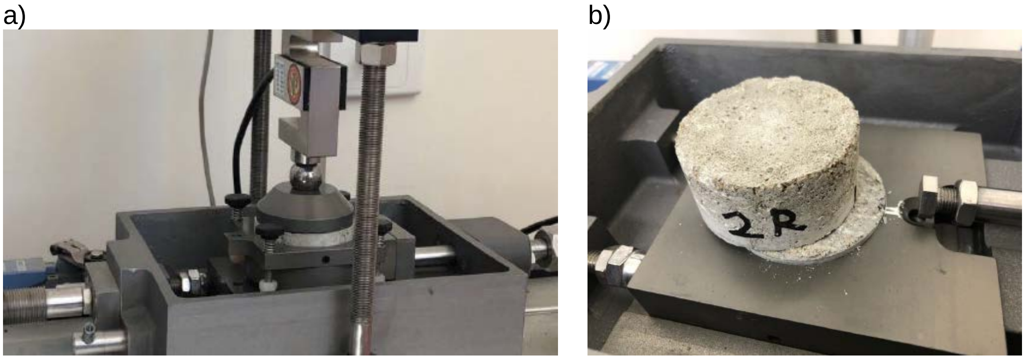


Figure 4: a) sample 2R during testing b) sample 2R after testing

RESULTS AND DISCUSSIONS – PART (A)

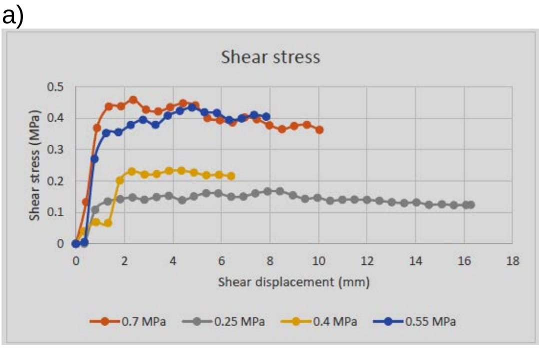
Each sample was tested with different loads and results are presented in three plots: normal stress, shear stress and dilution curve. These plots are based on the variation of shear displacement. As observed in the plots, normal loads which are constant for all samples are 2200 N, 1750 N, 1250 N and 750N. In terms of the magnitude of the normal stress on the samples, load 2200 N applies a normal stress of 0.7 MPa, load 1750 N yields a normal stress of 0.55 MPa, load 1250 N a normal stress of 0.4 MPa and then the normal stress of 0.25 MPa. Shear load and stress values for samples are different due to differences in the roughness of samples. Figures 5 to 7 are the results of this test for each sample.\

As shown in Figures 5 to 7, the shear stress curves first reach to their peak values with an almost linear trend and then remain almost constant as the residual stress by increasing the shear displacement. It is clear, the peak of shear stress increases with increasing the normal stress. It means, for example in the sample 1R, the peak of shear stress for 0.25 MPa normal stress is around 0.15 MPa while it is around 0.45 MPa for the normal stress of 0.7 MPa. This trend can be also observed for other samples.

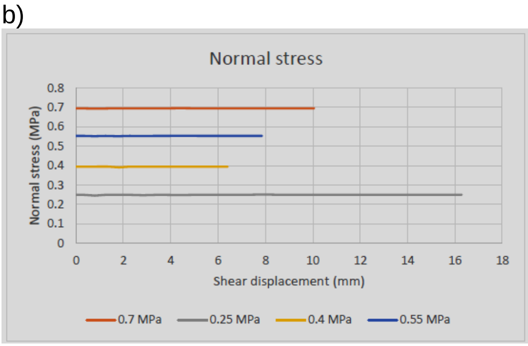
Roughness of samples affects the location on which each curve reaches the peak of shear stress. For instance, for sample 1R, the peak of shear stress for different loads happens at the shear displacement of around 1.8 mm while this value decreases for samples 2R and 3R. For the same value of normal stress, it is clear that the value of roughness in different samples also affects the peak value of shear stress.

In a general trend, dilation increases with the reduction of normal stress. In other words, highest vertical load of normal stress on each sample leads to the lowest value of dilation and vice versa. However, there are some exceptions in the plots which can be due to experimental error. Negative values for dilation curves on particular shear displacement locations for some loads means the compression during the shearing load on that location and the slope direction of the rock joint is negative at those particular shear displacements.

a)



b)



c)

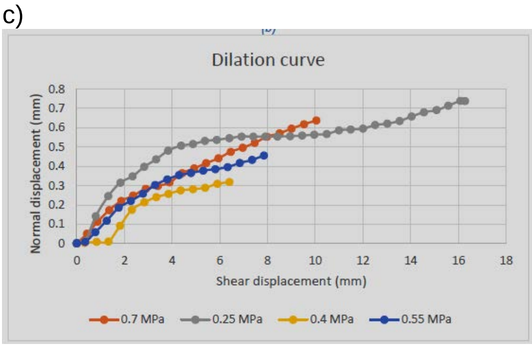


Figure 5: Experimental results for mould 1R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

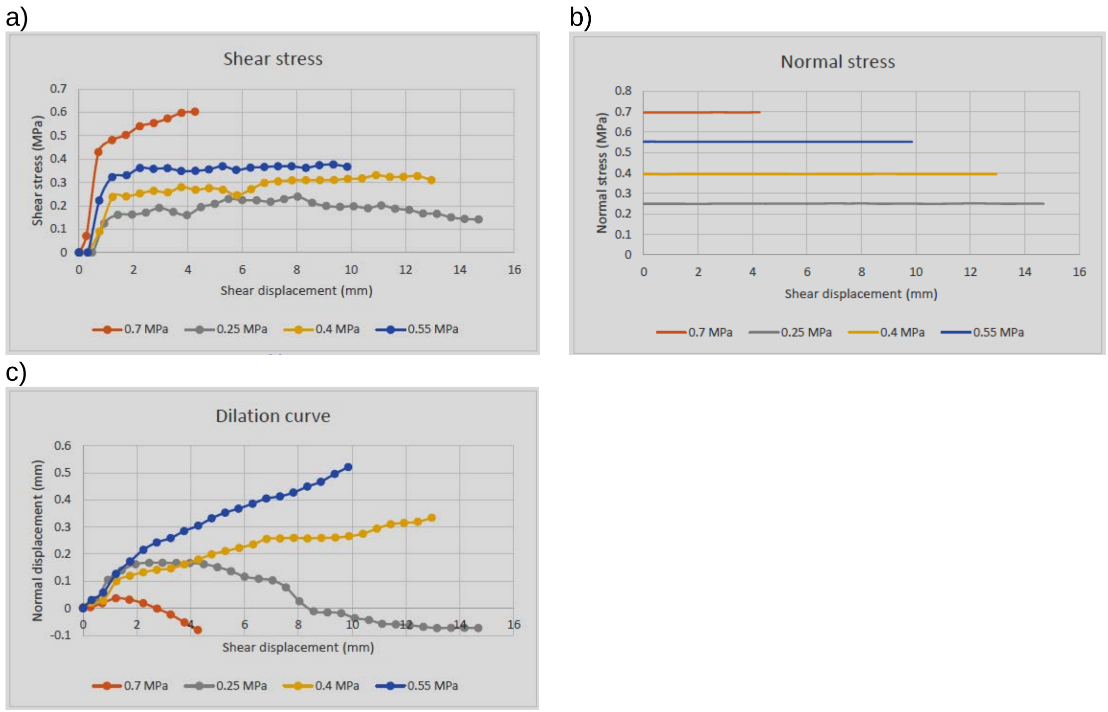


Figure 6: Experimental results for mould 2R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

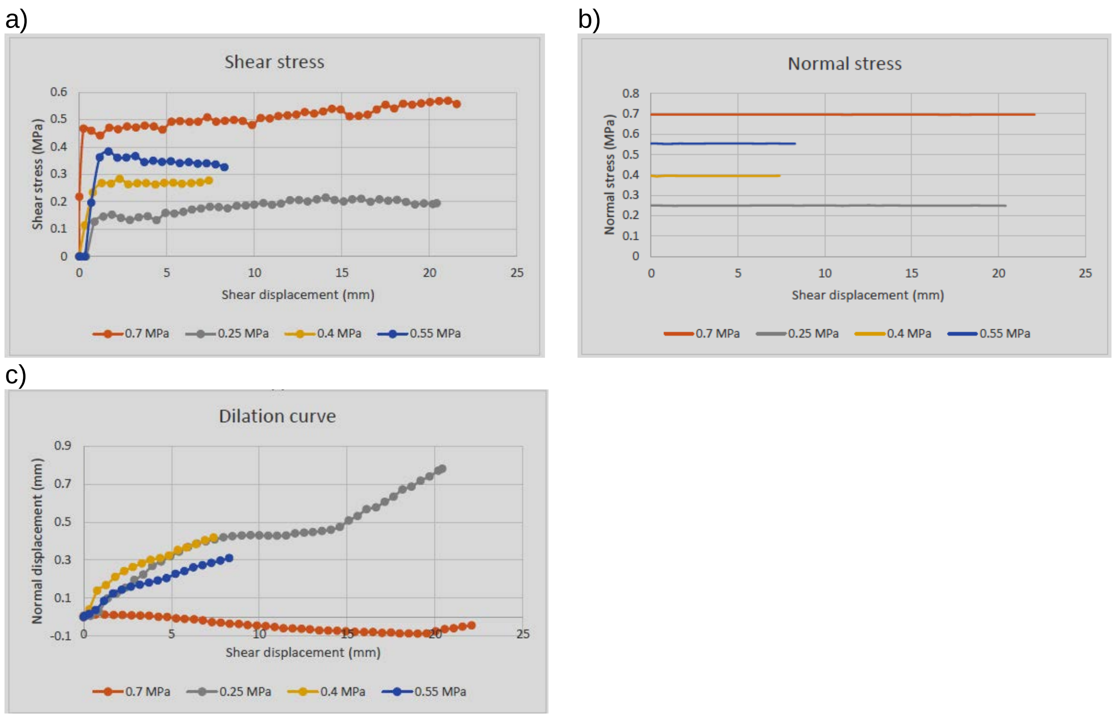


Figure 7: Experimental results for mould 3R a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

RESULTS AND DISCUSSIONS – PART (B)

The above results were obtained with the shear rate of 2 mm per minute. In a different test series, two moulds of 1R and 3R were selected for the experiment. The same testing procedure was applied on samples cast using these two moulds with the normal load of 1750 N but shear rate of 0.5 mm per minute and 1 mm per minute. The purpose was to investigate the effects of shear rate value on the shear stress, normal stress and dilation curve. The plots presented in Figures 8 and 9 are the results of these tests. They compare the results for samples 1R and 3R for different shear rates of 0.5 mm per minute, 1 mm/min with the previous results for these samples with a shear rate of 2 mm /min.

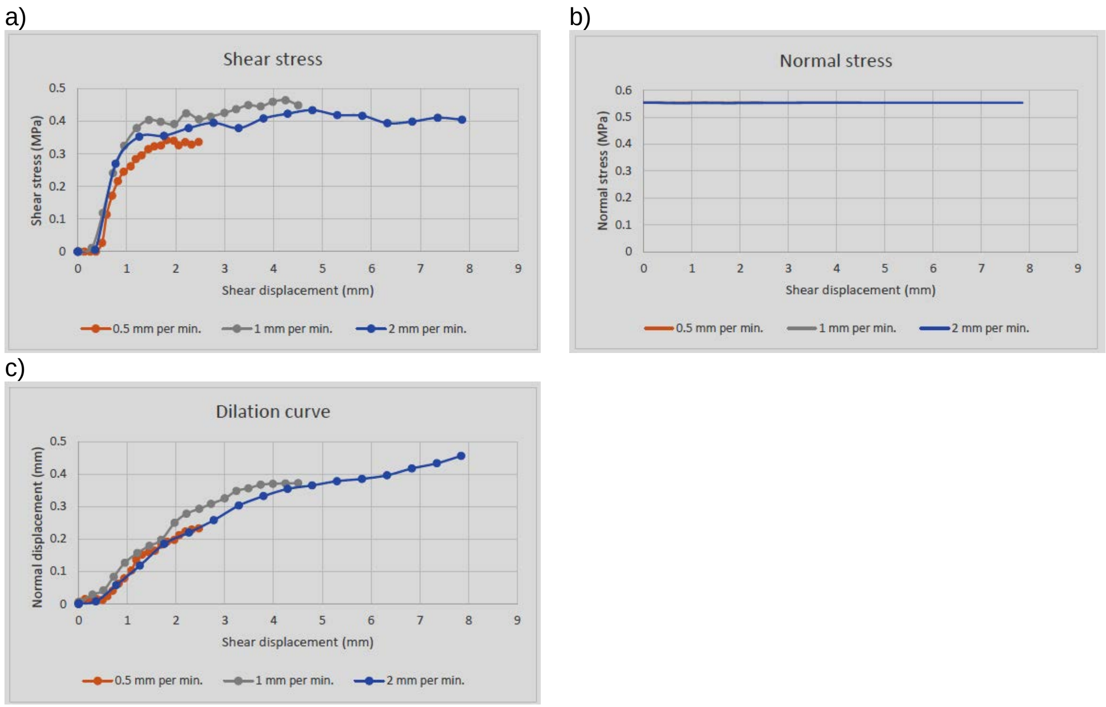


Figure 8: Experimental results for mould 1R with various shear rate values a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

As indicated in Figures 8(a) and 9(a) for the shear stress versus shear displacement plot, the shear rate affects the behaviour of shear stress curve against shear displacement. Usually the peak value of shear stress increases with increasing shear rate. As the shear rate increases, the frictional resistance which is presented by the joint surface becomes larger which causes the increasing shear strength of the joint.

For the shear rate of 0.5 mm per minute, the curve first increase rapidly and then remains nearly stable at the shear stress of around 0.35 MPa. This trend for the shear rate of 1 mm per minute is similar with the difference that the curve remains nearly constant at a higher shear displacement which is due to a higher shear rate. The peak value of shear stress at this rare is 0.48 MPa. For the 2 mm per minute shear rate, the curve experiences a higher shear displacement but its peak shear stress of around 0.43 MPa is slightly less than that for the 1 mm per minute.

Figures 8 and 9 (b) present the plot of normal stress against shear displacement for different shear rates. It is clear, all curves are flat with no change in normal stress which indicated that the tests were performed under a constant normal load. There is no change in the value of normal stress at different shear rates because all experiments were carried out under the same normal load of 1750 N which applies a constant normal stress of 0.55 MPa on the samples.

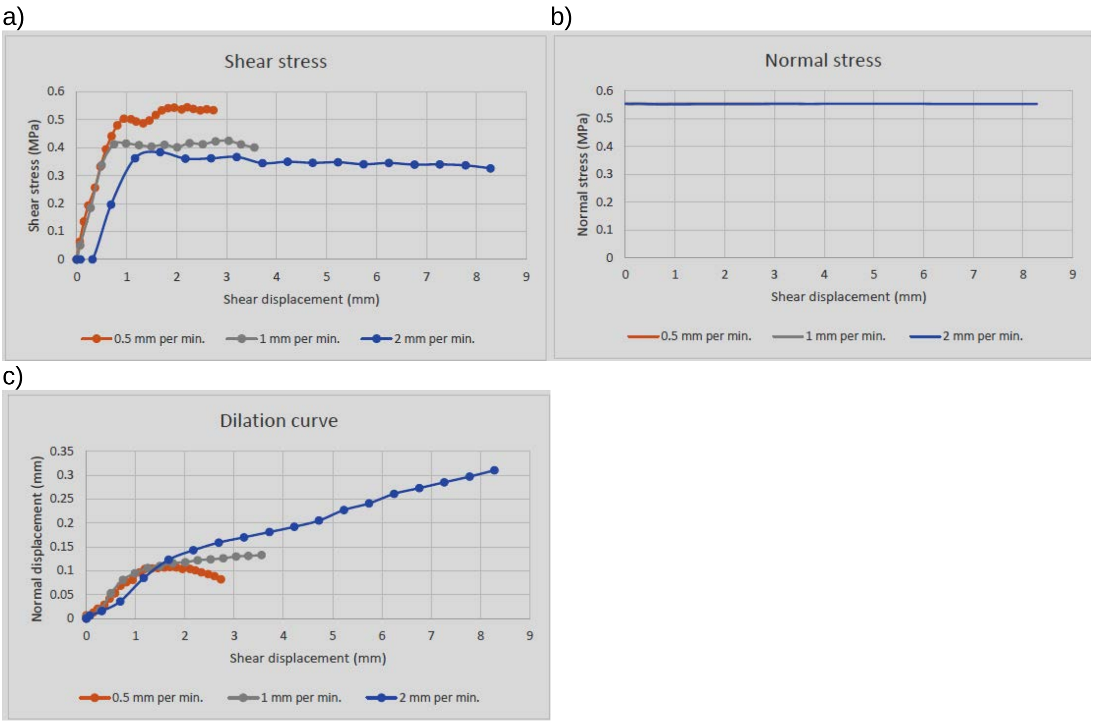


Figure 9: Experimental results for mould 3R with various shear rate values a) shear stress versus shear displacement b) normal stress versus shear displacement c) dilation versus shear displacement

Dilation curves are presented in Figures 8(c) and 9 (c) which is the plot of normal displacement against shear or horizontal displacement. It is obvious that all curves have an increasing trend along with the increasing shear displacement. For the shear rate of 0.5 mm pre minute, the curve reaches a normal displacement (dilation) of 0.22 mm in the shear displacement of 2.7 mm. The curve related to 1 mm per minute shear rate experiences a peak normal displacement of 0.37 mm in shear displacement of 4.5 mm. For the shear rate of 2 mm per minute, the curve reached a normal displacement of 0.46 mm in a shear displacement of 7.9 mm. As a general trend for this plot, it can be said that the dilation increases with increasing shear rate.

CONCLUSIONS

The aim of this research work was to investigate the effects of roughness, normal stress and shear rate on the unfilled joint shear behaviour under constant normal load condition. Three pair of moulds with different roughness was prepared to be used in shear testing machine. Four different normal loads were selected and were applied on the samples individually. This experiment was performed in two phases. At the first stage, each pair of sample was placed on the testing machine and was applied under a constant normal load and varying shear load. The shear rate was 2 mm per minute in this phase. This process was repeated 4 times. For the next phase of this experimental work, two of samples were selected for a different experiment. The testing process was almost similar to the first phase with the difference that this stage was carried out only for one normal load and two different shear rates of 0.5 mm per minute and 1 mm per minute. Following conclusions can be made from this experiment:

- The peak shear stress increases with increasing normal stress,
- Roughness value affects the location of the peak shear stress,
- The peak shear stress increases with the increase of the joint roughness,
- Dilation increases with the decrease of normal stress,

- The peak value of shear stress increases with the increase of shear rate,
- Dilation increased with increased in shear rate, and
- The peak dilation decreased with reduction of roughness.

In addition, it was shown that three dimensional printing technology is a useful tool in studying shear behaviour of real rock joints.

ACKNOWLEDGMENTS

The authors' wish to thanks Mr. Daniel Eising at the School of Civil Engineering and Surveying of the University of Southern Queensland for his assistance in the laboratory work.

REFERENCES

Lama, R D, 1978, Influence of clay fillings on shear behaviour of joints*, Proc. 3rd Congress. Int. Assoc. Eng. Geology*, Madrid, pp 27-34.

Patton, F D, 1966. Multiple modes of shear failure in rock, *In 1st ISRM Congress*, International Society for Rock Mechanics.

Ladanyi, B and Archambault, G, 1969, Simulation of shear behaviour of a jointed rock mass, *In the 11th US Symposium on Rock Mechanics (USRMS)*, American Rock Mechanics Association.

Barton, N, 1973, Review of a new shear-strength criterion for rock joints, *Engineering geology*, 7(4), pp 287-332.

Barton, N, 1976, Rock mechanics review*,* the shear strength of rock and rock joints*, International Journal of Rock Mechanics and Mining Science*, 13(Analytic).

Barton, N, 1986, Deformation phenomena in jointed rock*, Geotechnique*, 36(2), pp 147-167

Hoek, E, 1977, Rock mechanics laboratory testing in the context of a consulting engineering organization, *In International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, Elsevier.

Lecture, T R, 1983. Strength of jointed rock masses, *Gotechnique*, 33(3), pp 187-223.

Hoek, E, 1990. Estimating Mohr-Coulomb friction and cohesion values from the Hoek-Brown failure criterion, *In Intnl. J. Rock Mech. and Mining Sci. and Geomechanics Abstracts*.

Hoek, E and Brown, T, 1980, *Underground excavations in rock*.

Bandis, S A, Lumsden and Barton, N, 1981, Experimental studies of scale effects on the shear behaviour of rock joints, *In International journal of rock mechanics and mining sciences and geomechanics abstracts*, Elsevier.

Hencher, S, 1989, Laboratory direct shear testing of rock discontinuities, *Ground Engineering*, pp 24-31.

Kulatilake, P D, Wathugala and Stephansson, O, 1993. Joint network modelling with a validation exercise in Stripa Mine, Sweden, *In International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*. Elsevier.

Saeb, S and Amadei, B, 1992, Modelling rock joints under shear and normal loading, *In International journal of rock mechanics and mining sciences and geomechanics abstracts*. Elsevier.

Mirzaghorbanali, A, Nemcik, J and Aziz, N, 2014, Effects of cyclic loading on the shear behaviour of infilled rock joints under constant normal stiffness conditions*, Rock mechanics and rock engineering*, 47(4), pp 1373-1391.