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SHEAR STRENGTH PROPERTIES OF ARTIFICIAL ROCK JOINTS

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Abstract: The shear strength property of artificial rock joints with triangular and sinusoidal roughness was investigated in the laboratory by the aid of direct shear test machine. In particular, this paper includes literature review of past studies on shear strength properties of unfilled and infilled rock joints, experimental studies on shear strength properties of artificial rock joints with triangular, sinusoidal and plain roughness under various normal load and comparison between shear behaviour of these rock joints having different roughness patterns. This research presents the concepts development essential to envision the shear behaviour of rock slopes aided by artificial rock joints. It was concluded that the shear behaviour of rock joints is a function of normal stress, roughness value and pattern of asperity.

INTRODUCTION

Joints impact on the deformation and shear strength behaviour of rocks. The mechanical properties of rock mass are identical to that of joints in hard rocks (Lama, 1978). If the rock dilates while shearing, then the normal stress increases significantly and the shearing behaviour of rock becomes a function of the normal stiffness rather than the normal stress (Haque, A., 1999). The unfilled joint testing, through studies undertaken in past, can be categorised as joint testing of medium to hard rock joints or medium to soft rock joints, under constant normal stiffness. The key factors that affect the shear actions of infilled joints are summarized to be the type of joint, type of infill material, rate of shearing displacement, externally applied stiffness, horizontal confinement of specimen and characteristics of consolidation. Because of such a broad range of influence factors, in particular the shear behaviour of infilled joints with constant normal stiffness factors is very crucial to examine, since almost all previous tests under constant normal load were carried out. In this research study the shear strength of artificial rock joints, with different types of surface asperities, was investigated under low normal stress under unfilled and infilled joint conditions. The concepts developed in this research are valid for and applicable to the analysis of rock slopes.

METHODOLOGY

In this research, the shear behaviour of artificial rock joints was investigated. In order to cast artificial rock joints, the moulds were prepared at first. The specimens were prepared by incorporating five distinctive surfaces roughness. Each surface was comprised of different asperity height. The moulds were initially designed by the aid of Tinker CAD online 3D designing software, where each design was developed with the surface roughness that was required for casting corresponding specimen. Tinker CAD is an online application that allows designing and printing of 3D objects. It allows the use of distinctive tools including guides, references, grid lines and a number of hollow and solid 3D shapes. In this application, by combining and modifying the basic 3D shapes, the design of complex objects is

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developed. Figure 1 shows typical design that was developed using this application, where the final object after 3D printing can be seen. A total of four surfaces were designed and printed with different asperity patterns and roughness sizes. However, the plain surface did not need any design as for the purpose the plain board was used underneath PVC forms while casting plain surface.

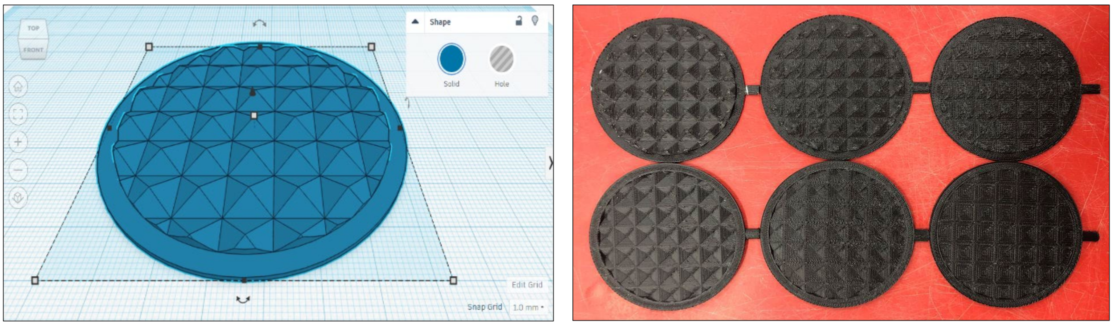


Figure 1: Design of typical asperity shape and 3D printed moulds

The diameter of specimen was 63.5 mm. The asperity height in each sample was different. for triangular asperities the asperity height of first specimen is 0.84 mm, in second specimen the height is 1.67 mm and in the third specimen the height of tooth is 2.5 mm. The angles of internal friction are 9.5, 18.5 and 26.5 degrees correspondingly. Moreover, the asperity height in sinusoidal mould (blue mould shown in Figure 2) is 1.67 mm and angle of internal friction is 18.5 degrees. In order to cast the specimen, the PVC tubes having 63.5 mm internal diameter were used. These tubes were used as forms for specimen. To obtain the required surface roughness and to attain the required shape of samples, the 3D printed moulds were attached at the bottom of PVC tube with the aid of general-purpose duct tape. Figure 3 presents the forms prepared for casting the samples.

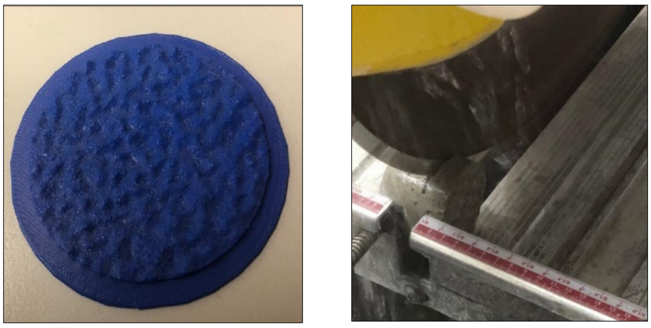


Figure 2: Sample preparation

Prior to filling PVC tubes with grout, the formwork release agent (shuttering oil) was applied to internal surface of PVC tubes to facilitate removal of specimen after hardening. Subsequently, the tubes were filled with grout prepared consisting of cement (0.6 kg), sand (2.004 kg) and water (0.432 kg), with yielding strength of 40 MPa. To cast the specimen, first the cement and sand were mixed in dry state, followed with water. The binding material used was ordinary Portland cement. The tubes were then filled before the initial setting time of cement. Each cylinder required 0.1 kg of cement, 0.334 kg of sand and 0.072 kg of water to yield 40 MPa strength sample.

The samples were removed from forms after 24 hours, they were placed in the curing room for proper hydration and strength development. The samples were marked for proper surface alignment upon form removal, so as to mitigate error during the shearing of specimen.

Figure 3: PVC forms

The specimens were subsequently trimmed to the required height in order to fit in the apparatus. For the purpose a concrete cutter was used and the sample was made ready to testing in direct shear testing machine.

TESTING RESULTS

In order to perform testing the ShearTrac-II direct shear testing machine was used. ShearTrac-II operates as an intelligent loading system. Its operations are based on the response received from horizontal and vertical force transducers and horizontal and vertical displacement transducers. It's hardware includes five major components consisting of a loading frame, test accessories, computer, keyboard and mouse and a display unit. The horizontal displacement limit of ShearTrac-II was 20 mm. The overall height was 560 mm; however, the cabinet height was 228 mm. The length of ShearTrac-II was 762 mm and the depth was 368 mm. The machine weighs of was 63 kg and consumes power of 110 volts. The ShearTrac-II direct shear testing machine is shown in Figure 4.

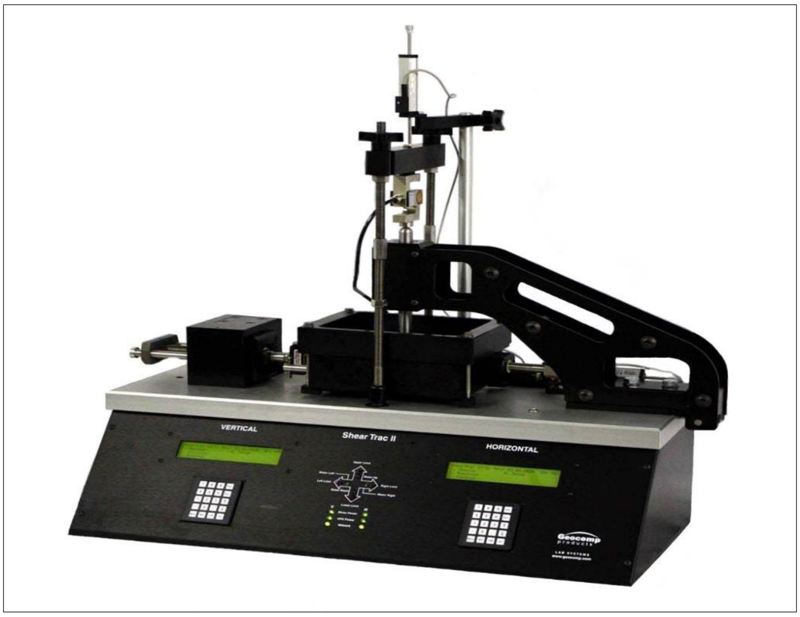


Figure 4: Shear Trac – II, Direct shear testing machine

In order to conduct the experimentation, the specimen was placed in a relatively flat box. Under the application of normal loading the box was split horizontally into two parts, where half box was held restrained while the other half was pushed with sufficient force and specimen experienced shear failure. Figure 5 shows the testing of a few samples. A total of five specimens with different types of asperity and surface roughness parameters were tested. These parameters are listed in Table 1.

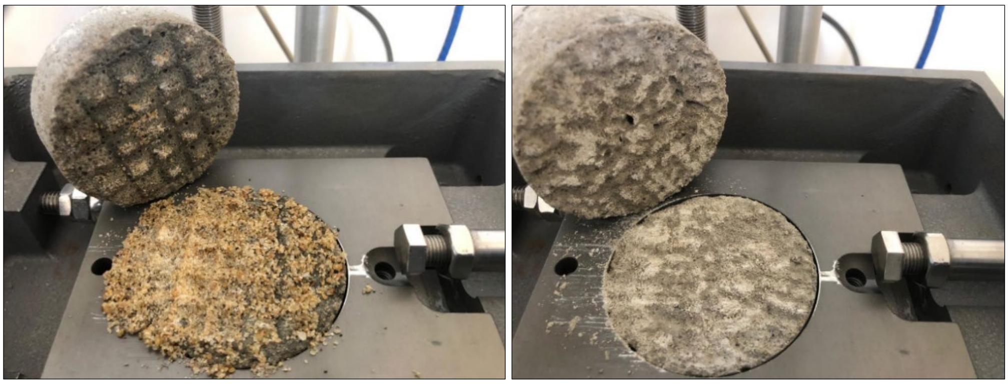


Figure 5: Direct shear test

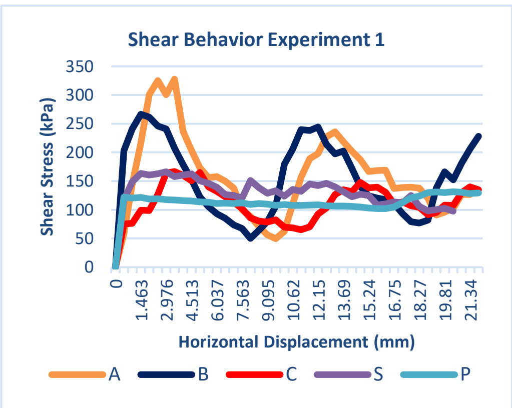
RESULTS AND ANALYSIS

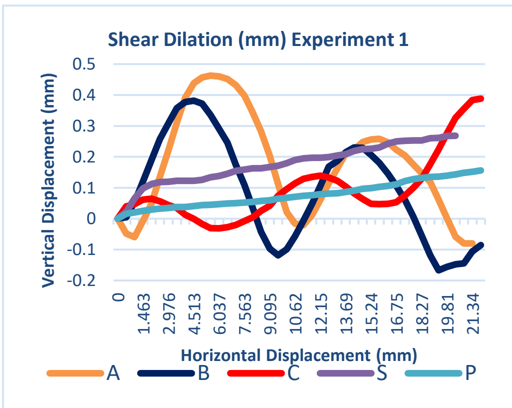
All samples were cast using 40 MPa strength mortar. The samples were tested having 28 days strength of curing. Table 1 shows the specification of samples used for unfilled and infilled experiments. In infilled joints, as infill material kiln dried especially graded fine sand was used. The water content for infill was 10 %t compared with the weight of infill material, where 10 gm of water was mixed with 100 gm of sand infill material preparation.

Table 1: Specimen specifications for unfilled and infilled tests

Sr. No	Specimen	Asperity Height (mm)	Angle of Internal Friction (Degree)	Strength (MPa)	Diameter (mm)
1	A- (Triangular-Prismatic)	2.5	26.5	40	63.5
2	B- (Triangular-Prismatic)	1.67	18.5	40	63.5
3	C- (Triangular-Prismatic)	0.84	9.5	40	63.5
4	S- Sinusoidal Surface	1.67	18.5	40	63.5
5	P- Plain Surface	0	0	40	63.5

The shear behaviour and dilation of unfilled and infilled tests are shown in Figure 6 and Figure 7.





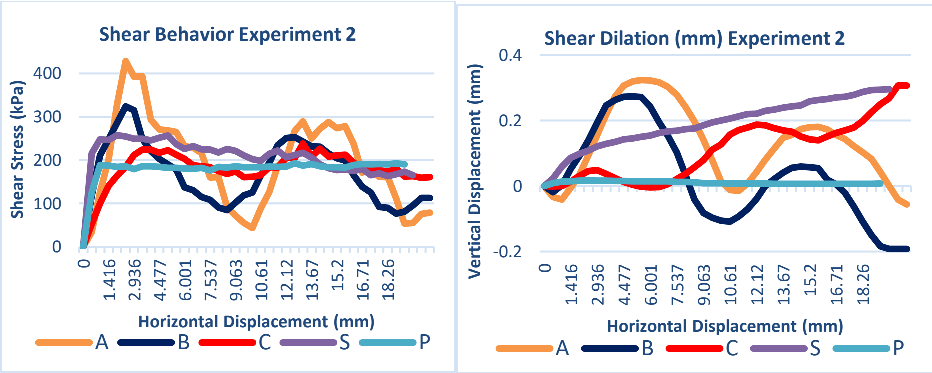


Figure 6: Shear behaviour and shear dilation of unfilled joints

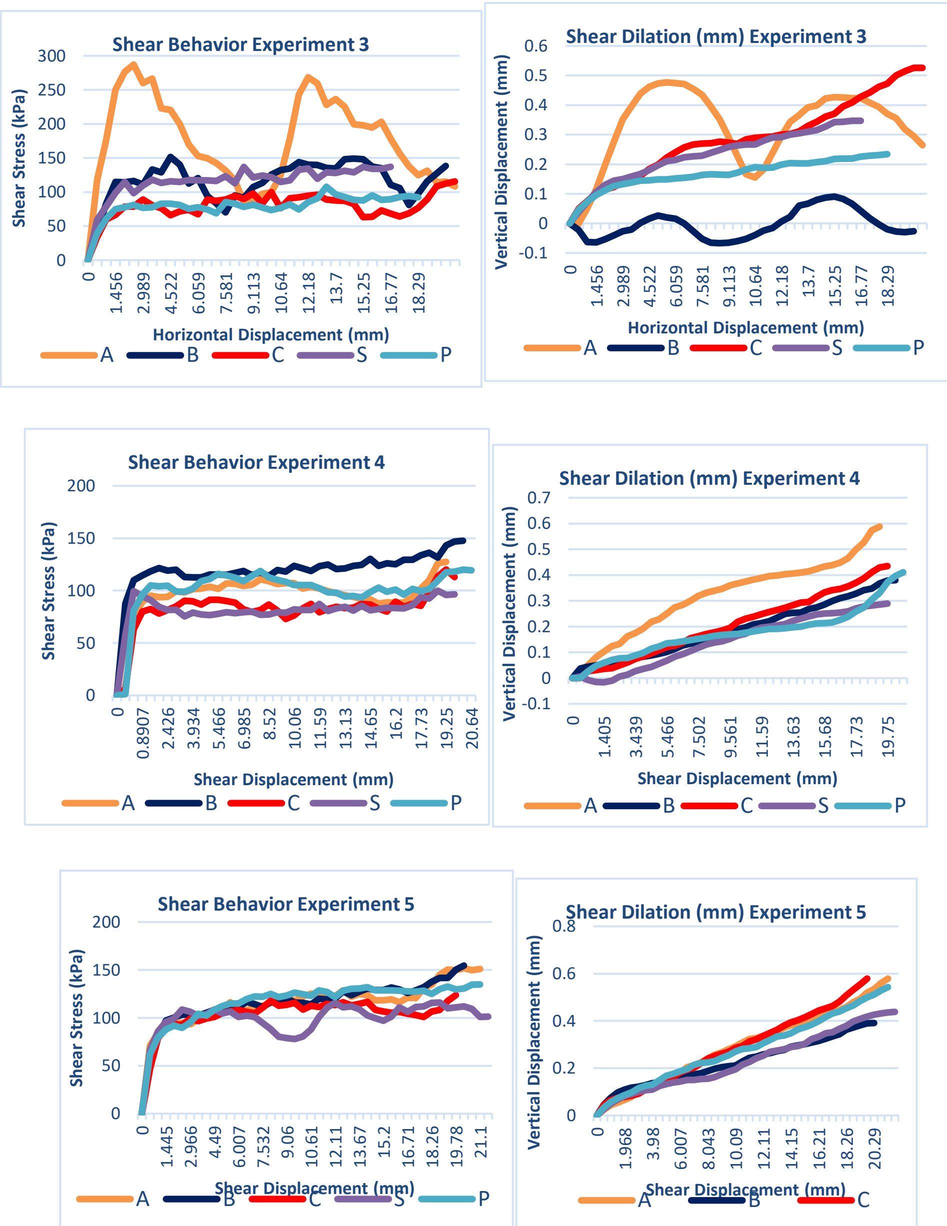


Figure 7: Shear behaviour and shear dilation of infilled joints

Experiment 1

Experiment 1 was conducted on unfilled rock joints under constant normal stress of 237 kPa and the corresponding normal load was 750 N. The asperity pattern of specimen A was triangular (prismatic) with asperity height of 2.5 mm. It was observed that the shear stress increased initially in a linear manner reaching the maximum value of 327.6 kPa at the horizontal displacement of 3.512 mm. The he minimum value of shear stress was 49.82 kPa at the horizontal displacement of 9.68 mm. Throughout the test, the shear stress varied consistently due to the variation in interlocking of asperities developed due to surface roughness between shearing surfaces. Due to this variation in interlocking of asperities, the value of friction between the surfaces also varied and hence the shear stress varied consistently throughout the test. The maximum shear stress was achieved when the top and bottom surfaces were entirely interlocked and the area of interaction was maximum as shown in Figure 8 (a). The shear stress changes between maximum and minimum value, was induced due to the variation in surface friction between minimum and maximum interaction area. This effect can be seen in the Figure 8 (b). At the minimum shear stress value the interlocking between the top and bottom surfaces was minimum as shown in Figure 8 (c).

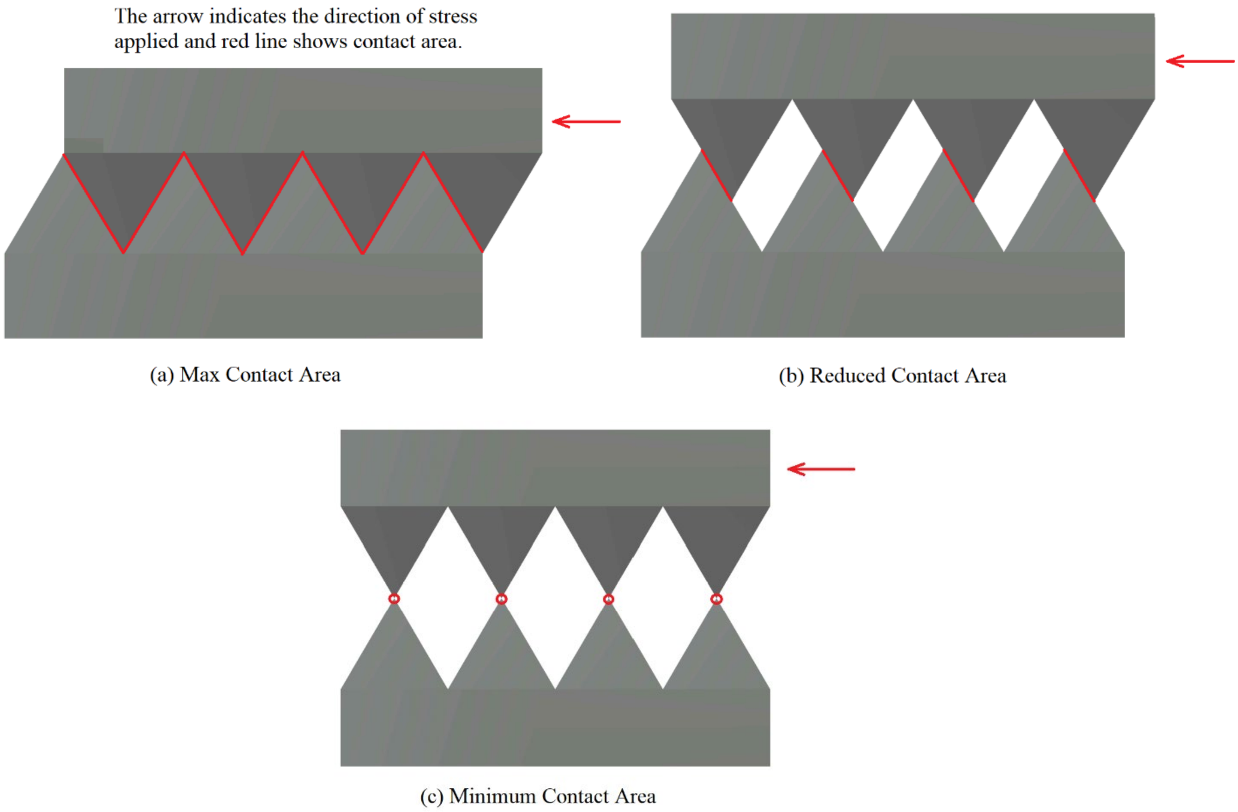


Figure 8: Interlocking of surfaces, designed in AutoCAD

Therefore, it is concluded that, as the interlocking of surfaces due to asperity height is increased the shear stress increases and as the interlocking decreases the shear stress decreases. Figure 6 shows the dilation behaviour of experiment 1, which that the pattern of dilation is to some extent identical to the shape of asperity. The negative values in the graph shows the compression due to normal stress; the positive value shows the amount of dilation that took place during shearing. The amount of dilation was greatest when the first asperity of bottom surface slid against the first asperity of top surface, however, it reduced in the sliding stage of subsequent asperities. The reason behind this behaviour is the surface damage while shearing, which reduced the amount of dilation. However, the damage of surface was not significant.

The asperity pattern of specimen B was triangular (prismatic) with asperity height of 1.67 mm. The shear behaviour of sample B was almost identical to the shear behaviour of sample A, where the stress increased initially in a linear manner and reaching the maximum value of 266.4 kPa at the horizontal displacement of 1.413 mm. The minimum value of shear stress was 50.39 kPa at the horizontal displacement of 8.111 mm. However, the asperity height and angle of internal friction of sample B was less compared with sample A. This due to the fact that the maximum shear stress of sample B was less than the maximum shear stress of sample A.

The asperity pattern of specimen C was also triangular (prismatic) with asperity height of 0.84 mm. It was observed that the shear behaviour of sample C was also nearly similar to the shear behaviour of samples A and B, where the stress increased initially in a linear manner reaching the maximum value of 166.7 kPa at the horizontal displacement of 3.482 mm and the minimum value of shear stress was 65.42 kPa at the horizontal displacement of 11.16 mm. This behaviour in sample C is also similar to sample A and B. However, the asperity height and the angle of internal friction of sample C was further reduced compared with the sample A and B. This was attributed to the fact that the maximum shear stress of sample C is less compared with the shear stress of both samples A and B.

The asperity height of specimen C was 0.84 mm. The dilation graph of experiment 1 in Figure 6 shows the maximum value of dilation of 0.064 mm at 1.976 mm of horizontal displacement, where there was no significant damage to the surface due to shearing. The value of dilation increased up to 0.1392 mm at 12.16 mm of horizontal displacement. Also, the dilation reached a value of 0.388 mm in the end of test at a horizontal displacement of 21.37 mm. The reason behind this dilation behaviour is that as the test progressed, the surface began to get damaged, due to the accumulation of damaged particles between the shearing surfaces. As the test progressed further, the accumulation of particles also increased between the shearing surfaces. These accumulated particles resulted in the incremental dilation as the accumulation increased. This effect can be seen in Figure 9.

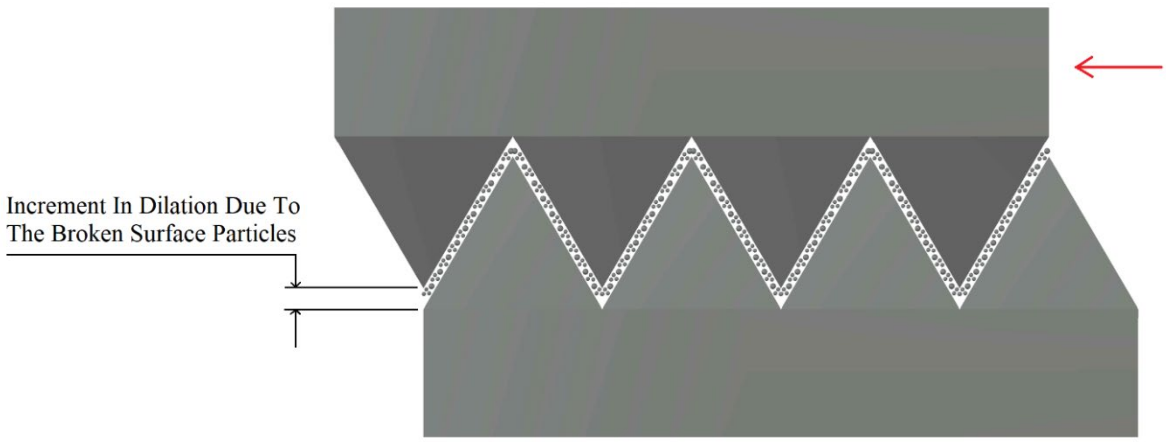


Figure 9: Increment in dilation of unfilled joint due to damaged surface particles, designed in AutoCAD

The shear behaviour of sinusoidal "S" joint and plain "P" joint shows linear increment in shear stress at first and reached the peak. It varied consistently and reduced as the shear displacement progressed. The minimum shear stress of sinusoidal joint was 97.762 kPa at 20.31 mm of shear displacement. The reason behind this depression in the shear graph was caused by the consistent reduction in the shear strength of the rock joint due to the consistent damage of the surface. The plain surfaces do not interlock as the asperity height was negligible because of less friction between surfaces. This is the reason why the plain surface has the minimum shear strength compared with other asperities. Moreover, the broken surface particles were also a reason of reduction of shear strength, as these particles assisted in the sliding of surfaces and actsa as infill in clean joint after some shear displacement.

The dilation behaviour of sinusoidal and plain joint shows steady increment in the value of dilation compared to the initial to final dilation. This is due to the consistent breaking of the surface due to shear and accumulation of broken particles between the shearing surfaces of rock joints. At the initial stage the dilation was minimum because of the minimal the damaged particles. However, the accumulation of broken particles increased as shearing progressed. This behaviour was identical to the one shown in Figure 9. These broken particles were also the reason of reduction in shear strength, as these particles assisted in the sliding of surfaces and acted as infill in clean joint.

Experiment 2

Experiment 2 was performed under unfilled joint condition and constant normal loading. The normal stress applied was 295 kPa and results of experiment 2 can be seen in Figure 6. The behaviour of each type of surface was analysed and explained in detail in experiment 1. Therefore, those points will not be repeated in the subsequent experiments. The only behaviours that are different, compared with the behaviours shown in experiment 1, are analysed and are explained in detail subsequently.

In experiment 2, the individual behaviour of each specimen was identical to the corresponding sample with similar surface asperity in experiment 1. The shear stress of samples A and B reached to the maximum value in linear manner. The interlocking of surfaces was maximum at maximum shear stress and it reduced in similar way as for samples A and B in experiment 1. However, the values of maximum shear stress were noted to be 428.6 kPa for sample A and 324 kPa for sample B. This stress was significantly higher compared to the maximum stress obtained of samples A and B in experiment 1. Similarly, the maximum shearing stress for samples C, S and P was higher than the one of samples C, S and P in experiment 1. This rise of maximum shear stress was the result of application of additional 58 kPa of normal stress to the specimens in experiment 2. This additional normal stress imposed more pressure between the shearing surfaces. This additional pressure induced higher friction between the sliding surfaces. To slide surfaces with lower surface friction requires less force compared to the surfaces with higher friction. Therefore, due to this increment in friction a higher shearing stress was required to slide the joint surfaces.

Experiment 3

In experiment 3, the constant normal stress was 237 kPa and joint was sheared with infill having thickness of 0.5 times asperity height. Height of infill used in experiment 3 for corresponding samples is given in Table 2.

In this test, the shear behaviour of asperities is changed compared with the results of experiment 1. The reason of this change in shear behaviour is the infill material between the shearing surfaces. The shearing material assists the surfaces to slip at lower shear stress even if the angle of internal friction is greater. The existence of infill material (in this case, non – cohesive) between surfaces mitigates the friction between surfaces. The shear strength of the joint was reduced compared with the shear strength of joint without infill material. In this case where the joint is infilled, some of the shear strength is controlled by the infill material and some is controlled by the sharp asperity. Figure 10 shows the shear behaviour of experiment 3. The shear behaviour of sample A shows maximum shear strength compared to other samples. It is noted that the maximum shear stress induced in sample A while shearing is 284 kPa at 2.493 mm of shear displacement. The maximum shear stress of specimen A in experiment 3 is less compared with the maximum shear stress of specimen A in experiment 1, even the specimen specifications are same, it is because the joint tested in experiment 1 is unfilled joint, however, the joint tested in experiment 3 is infilled joint and it is the infill material that has reduced the maximum shearing strength in experiment 3. The maximum shearing strength of other specimens in experiment 3 is also quite low compared with the rest of specimens in experiment 1, and it is also reduced due to the infill material. Whereas the normal stress in both experiments was equal and constant. Therefore, it is evident that the shear strength of rock joint decreases due to infill material. Figure 7 shows the dilation behaviour of experiment 3. It shows that the dilation of samples A and B in experiment 3 is quite similar to the dilation behaviour of samples A and B in experiment 1 and 2. There is no significant change in the behaviour of vertical displacement of samples A and B in experiment 3, because the shape of asperity is uniform and the height of asperity is large enough, also the thickness of infill layer is not sufficient to alter the dilation behaviour of samples A and B. The dilation behaviour of samples A and B show that the shearing is controlled by both the sharp asperities and the infill material. However, the behaviour of vertical displacement of sample C was influenced by the infill material and it can be noted that the dilation pattern of sample C in experiment 3 did not vary as it varied in experiment 1 and 2, instead it is identical to the behaviour of plain surface. It is because the angle of internal friction is quite low as height of asperity is not enough and the thickness of infill layer is higher and the dilation graph shows that the shear behaviour of sample C is mostly controlled by infill material compared with the asperities. The samples S and P have shown the similar behaviour as in experiment 1 and 2. It is because infill thickness has no significant effect on dilation behaviour of the surfaces due to the low internal friction angle. In summation, the shear graph shows consistent variation in shear stress of all asperities except plain surface. Therefore, it is evident that still the shear behaviour, to some extent, is controlled by sharp asperities.

Table 2: Infill specification

Infill height in experiment 3					
Sr. No	Sample/Asperity	Unfilled Asperity Height (mm)	Infill Height (mm) 0.5*H of Asperity	Total Height (mm)	Asperity Shape
1	A	2.5	1.25	3.75	Triangular
2	B	1.67	0.835	2.505	Triangular
3	C	0.84	0.42	1.26	Triangular
4	S	1.67	0.835	2.505	Sinusoidal
5	P	0	1	1	Plain
Infill height in experiment 4					
Sr. No	Sample/Asperity	Unfilled Asperity Height (mm)	Infill Height (mm) 1*H of Asperity	Total Height (mm)	Asperity Shape
1	A	2.5	2.5	5	Triangular
2	B	1.67	1.67	3.34	Triangular
3	C	0.84	0.84	1.68	Triangular
4	S	1.67	1.67	3.34	Sinusoidal
5	P	0	2	2	Plain
Infill height in experiment 5					
Sr. No	Sample/Asperity	Unfilled Asperity Height (mm)	Infill Height (mm) 1.5*H of Asperity	Total Height (mm)	Asperity Shape
1	A	2.5	3.75	6.25	Triangular
2	B	1.67	2.505	4.175	Triangular
3	C	0.84	1.26	2.1	Triangular
4	S	1.67	2.505	4.175	Sinusoidal
5	P	0	3	3	Plain

Experiment 4

In experiment 4 the constant normal stress was 237 kPa and joint was sheared with infill having thickness equal to asperity height. Height of infill used in experiment 4 for corresponding samples is given in Table 2.

In this test, the shear behaviour of asperities was changed compared with the results of experiment 3. The maximum shear strength of all samples in experiment 4 was reduced significantly, as shown in Figure 7. In the shear behaviour graph of experiment 4, the pattern of shearing stress for all the specimen was no longer varying as was varied in experiments 1, 2 and 3. However, the variation was very little, which has very less influence of the asperity pattern. Instead this variation was mainly the function of internal friction of infill material. The dilation graph of experiment 4 in Figure 7 shows that the dilation of sample A was greater compared to other specimens and occurred due to the highest asperity height and over laying and accumulation of infill material. As the thickness of infill was greater, there was minimal contact of sharp asperities and there was minimal damage to the asperities. The increment in dilation at the end of test was significant and it was not because of the accumulation of damaged particles but instead occurred due to the over-riding of infill particles. This behaviour is shown in Figure 10. Moreover, the infill material interlocked partially with the top surface and partially with the bottom surface, leaving minimal damage to the interacting surfaces of rock joints. The normal stress was not significant, however, if greater normal stress was applied that could damage the surfaces as well. In this case with infill between shearing surfaces the normal stress required to shear the surfaces would be significantly large. From the discussion above, it is concluded that as the thickness of infill layer increases the shear behaviour becomes the function of the shear parameters of infill material rather than the asperities.

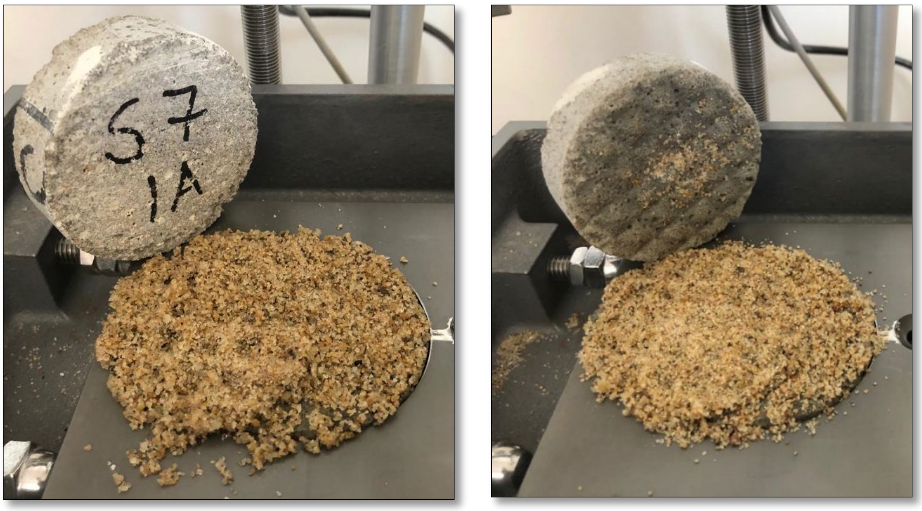


Figure 10: Sample A with infill height equal to asperity height

Experiment 5

In experiment 5 the constant normal stress was 237 kPa and joint was sheared with infill having thickness equal to 1.5 times the asperity height. Height of infill used in experiment 5 for corresponding samples is given in Table 2.

The shear behaviour of experiment 5 in Figure 7 shows identical maximum shear stress for all samples, where the thickness of infill layer was greater than the asperity height. As the surface asperities did not interact with each other, so the shear strength of these samples was the function of infill material rather than that of joint surface asperities. Hence, the maximum shear strength of each specimen in experiment 5 was significantly low compared with the shear strength of specimens tested in experiment 1, where the applied normal stress was exactly same. Therefore, it was concluded that the shear strength of rock joint reduces as the depth of infill material increases and a point reaches where the shear strength of joint becomes the function of infill material entirely and the shear strength of surfaces becomes negligible in joint strength.

CONCLUSIONS

Interlocking of joint surface plays vital role in increment or reduction of shear strength in rock joints. As roughness height and angle of internal friction in sample B is less than the one in sample A, therefore, the maximum shearing stress was less than the maximum shear stress of sample A in experiments 1 and 2. Therefore, it is concluded that the asperity height and angle of internal friction have significant influences on the shear strength of the rock joint. The greater is the surface roughness the greater is the shear strength. This only applies in case of uniform interaction between shearing surfaces and joint being unfilled. In case of non-uniform interlocking between shearing surfaces and high roughness, the shear strength will be significantly reduced, which is clearly been demonstrated in Figure 7 (c) where there is minimum interlocking and interaction area between shearing surfaces. Moreover, it is also concluded that, the joint remains unfilled until the surfaces are damaged. The evidence can be seen in the Figure 8. Furthermore, it is determined that the shear resistance is greatly influenced by asperity height, angle of internal friction and interlocking of shearing surfaces. Additionally, the joint dilation increases due to shearing of surfaces and accumulation of damaged particles. Therefore, it is concluded that the maximum dilation might be greater than the maximum height of infill layer. The greater the asperity height the greater the dilation occurs in uniform asperity patterns; however, this is not the case where the pattern of asperities is irregular.

The experiments conducted on infilled joints revealed that the shear strength of rock joint decreases due to infill material. The shear behaviour depends on the thickness of infill material, if the thickness of infill layer is high then the shear is controlled by infill. However, if the thickness of the infill is less and the asperity height is greater, then the shear strength is mainly controlled by sharp asperities of the joint surface. As the thickness of infill layer increases, then the increment of infill height increases and the shear behaviour becomes the function of shear parameters of infill material. The shear strength of rock joint reduces as the depth of infill material increases and a point reaches where the shear strength of joint becomes the function of infill material entirely and the shear strength of joint surfaces become negligible in joint strength.

REFERENCES

Bandis, S., Lumsden, A.C. and Barton, N.R., 1981, February. Experimental studies of scale effects on the shear behaviour of rock joints. In International journal of rock mechanics and mining sciences geomechanics abstracts (Vol. 18, No. 1, pp. 1-21). Pergamon press.

Barla, G., Forlati, F. and Zaninetti, A., 1985, September. Shear behaviour of filled discontinuities. In Proceedings of the international symposium on fundamentals of rock joints, Bjorkliden (pp. 163-172).

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

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

Barton, N., 1976, September. The shear strength of rock and rock joints. In International Journal of rock mechanics and mining sciences Geomechanics abstracts (Vol. 13, No. 9, pp. 255-279). Pergamon.

Benmokrane, B. and Ballivy, G., 1989, January. Laboratory study of shear behaviour of rock joints under constant normal stiffness conditions. In The 30th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.

Crawford, A.M. and Curran, J.H., 1981, December. The influence of shear velocity on the frictional resistance of rock discontinuities. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 18, No. 6, pp. 505-515). Pergamon.

Curran, J.H. and Leong, P.K., 1983, January. Influence of shear velocity on rock joint strength. In 5th ISRM Congress. International Society for Rock Mechanics and Rock Engineering.

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

Eurenius, J. and Fagerstrom, H., 1969. Sampling and testing of soft rock with weak layers. Géotechnique, 19(1), pp.133-139.

Goodman, R.E., 1970. The deformability of joints. In Determination of the in situ Modulus of Deformation of Rock. ASTM International.

Goodman, R.E., 1976. Methods of geological engineering in discontinuous rocks, West publishing, St. Paul, Minn. USA.

Haberfield, C.M. and Seidel, J.P., 1999. Some recent advances in the modelling of soft rock joints in direct shear. Geotechnical Geological Engineering, 17(3-4), pp.177-195.

Haque, A., 1999. Shear behaviour of soft rock joints under constant normal stiffness. PhD thesis, University of Wolongong, Australia, P.271

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

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

Hoek, E., 1990, June. Estimating Mohr-Coulomb friction and cohesion values from the Hoek-Brown failure criterion. In Intnl. J. Rock Mech. Mining Sci. Geomechanics Abstracts (Vol. 12, No. 3, pp. 227-229).

Hoek, E., 1977, March. Rock mechanics laboratory testing in the context of a consulting engineering organization. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 14, No. 2, pp. 93-101). Pergamon.

INDRARATNA, B., 1993. Experimental Study of Shear Behaviour of Rock Joints Under Constant Normal Stiffness. Int. J. Rock Mech. Min. Sci. Geomech. Abstr.., 34(3), p.534.

Kanji, M.A., 1974, September. Unconventional laboratory tests for the determination of the shear strength of soil-rock contacts. In Proc. 3rd Congr. Int. Soc. Rock Mech., Denver (Vol. 2, pp. 241-247).

Kodikara, J.K. and Johnston, I.W., 1994, August. Shear behaviour of irregular triangular rock-concrete joints. In International journal of rock mechanics and mining sciences geomechanics abstracts (Vol. 31, No. 4, pp. 313-322). Pergamon.

Kulatilake, P.H.S.W., Wathugala, D.N. and Stephansson, O., 1993, October. Joint network modelling with a validation exercise in Stripa Mine, Sweden. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 30, No. 5, pp. 503-526). Pergamon.

Kulatilake, P.H.S.W., Shou, G., Huang, T.H. and Morgan, R.M., 1995, October. New peak shear strength criteria for anisotropic rock joints. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 32, No. 7, pp. 673-697). Pergamon.

Kutter, H.K. and Rautenberg, A., 1979, January. The residual shear strength of filled joints in rock. In 4th ISRM Congress. International Society for Rock Mechanics and Rock Engineering.

Ladanyi, B. and Archambault, G., 1977, July. Shear strength and deformability of filled indented joints. In Proc International Symposium on the Geotechnics of Structurally Complex Formations. Capri (Vol. 1, No. 1, pp. 317-326).

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

Lam, T.S. and Johnston, I.W., 1989. Shear behavior of regular triangular concrete/rock jointsevaluation. Journal of geotechnical engineering, 115(5), pp.728-740.

Lama, R.D., 1978. Influence of clay fillings on shear behaviour of joints. In: Division of Applied Geomechanics, editor/s. Proceedings III International Congress I.A.E.G.; Sep 4-8, 1978; 1978. 27-34. http://hdl.handle.net/102.100.100/299705?index=1

Leichnitz, W., 1985, October. Mechanical properties of rock joints. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 22, No. 5, pp. 313-321). Pergamon.

Mirzaghorbanali, A., Nemcik, J. and Aziz, N., 2014. Effects of shear rate on cyclic loading shear behaviour of rock joints under constant normal stiffness conditions. Rock mechanics and rock engineering, 47(5), pp.1931-1938.

Obert, L., Brady, B.T. and Schmechel, F.W., 1976. The effect of normal stiffness on the shear resistance of rock. Rock mechanics, 8(2), pp.57-72.

Ohnishi, Y. and Dharmaratne, P.G.R., 1990. Shear behaviour of physical models of rock joints under constant normal stiffness conditions. Rock Joints, Balkema, Rotterdam, pp.267-273.

Papaliangas, T., Hencher, S.R., Lumsden, A.C. and Manolopoulou, S., 1993, April. The effect of frictional fill thickness on the shear strength of rock discontinuities. In International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts (Vol. 30, No. 2, pp. 81-91). Pergamon.

Paulino Pereira, J., 1990. Mechanics of filled discontinuities. In International conference on mechanics of jointed and faulted rock (pp. 375-380).

Pereira, J.P., 1990. Shear strength of filled discontinuities. Rock Joints. Balkema, Rotterdam, pp.283-287.

Phien-Wej, N., Shrestha, U.B. and Rantucci, G., 1990. Effect of infill thickness on shear behaviour of rock joints. Rock joints, pp.289-294.

Saeb, S. and Amadei, B., 1992, May. Modelling rock joints under shear and normal loading. In International journal of rock mechanics and mining sciences geomechanics abstracts (Vol. 29, No. 3, pp. 267-278). Pergamon.

Tulinov, R. and Molokov, L., 1971, September. Role of joint filling material in shear strength of rocks. In International Society of Rock Mechanics, Symposium on Rock Fracture, Nancy (Vol. 2, p. 13).

Van Sint Jan, M.L., 1990. Shear tests of model rock joints under stiff normal loading. Rock joints. Balkema, Rotterdam, pp.323-327.

Xu, S., 1989. The relationship between stress and displacement for rock surfaces in shear (Doctoral dissertation, Imperial College London (University of London)).