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Shear behaviour of regular and irregular rock joints under cyclic conditions

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ABSTRACT
Rock masses often have sets of joints or fractures and almost all failures are due to the presence of these discontinuities. Natural joints have irregular surfaces, and the correct evaluation of shear strength and deformation of these irregular joints is very important for the analysis and engineering design of rock structures. These joints are often subjected to dynamic loads because of earthquake and blasting during mining and rock cutting. Hence, it is important to correctly evaluate the shear behaviour of regular and irregular rock joints under dynamic conditions. In the present study, synthetic rock joints are prepared with plaster of Paris and regular joints are replicated by keeping regular asperities with asperity angles 15°-15° and 30°-30°. Irregular rock joints are prepared by keeping the asperity angles 15°-30° and 15°-45°. The sample size and amplitude of roughness are kept constant for both regular and irregular joints, at 298×298×125 mm and 5 mm respectively. Shear tests have been performed on these joints with a large scale direct shear testing machine by keeping the frequency and amplitude of shear loads constant under cyclic load conditions and varying the normal stress. The shear strength of rock joints increases with increase in the asperity angle and normal load during the first cycle of shearing. With the increase in the number of shear cycles, the shear strength reduces for all the asperity angles, but the rate of reduction is greater in the case of high asperity angles. Test results indicate that the shear strength of irregular joints is higher than regular joints at different cycles of shearing at low normal stresses. The mechanism of the shearing for regular and irregular joints is different under the cyclic conditions at low normal stresses. Shearing and degradation of joint asperities on regular joints between loading and unloading are the same, but for irregular joints they are different at low normal stresses. Shear strength and joint degradation are more significant on the slope of asperity with higher angles on the irregular joint, until two angles of asperities become equal during the cycle of shearing and it starts to behave like a regular joint.
KEYWORDS: Cyclic shear behaviour; shear strength; regular joint; irregular joint; joint dilation

1. INTRODUCTION

Shear stress and deformation behaviour of rock joints play an important role for design and analysis of underground structures, foundation, slope stability and risk assessment of underground disposal. Many researchers in the field of rock mechanics and rock engineering have presented the shear behaviour of jointed rock, based on peak stress-strain along the joint under unidirectional or monotonic (static) shear loads. However, joints are subjected to dynamic loads due to earthquake, blasting, and vibration, which can be simulated as shear along the joint under cyclic loads. In this condition, load direction is reversed on the shearing plane repeatedly. In the present work, a physical model is prepared in order to examine the shear behaviour of a natural jointed rock mass. In the past shear behaviour of regular joints under cyclic conditions was studied by many researchers (Huang et al.,1993; Hutson & Dowding, 1990; Homand et al., 2001; Jafari et al., 2003; Indraratna et al., 2012; Mirzaghorbanali et al., 2013; Niktabar et al., 2015). However, joints in the rock mass are irregular and have different roughness. In the present study regular and irregular joints with asperity angles 15°-15° and 30°-30° and 15°-30° and 15°-45° are prepared accordingly. Joints with irregular asperities are more representative and closer to natural joints. Each cycle is divided into four stages as described by Lee et al. (2001), such as forward advance (FA), forward return (FR), backward advance (BA), and backward return (BR); for better understanding, the four stages are illustrated in Figure 1. The FA movement at first shear cycle is similar to static or monotonic shear loads.

To study the effect of irregular asperities on the shear behaviour of rock joints under cyclic conditions, a series of tests were performed on regular and irregular jointed samples.

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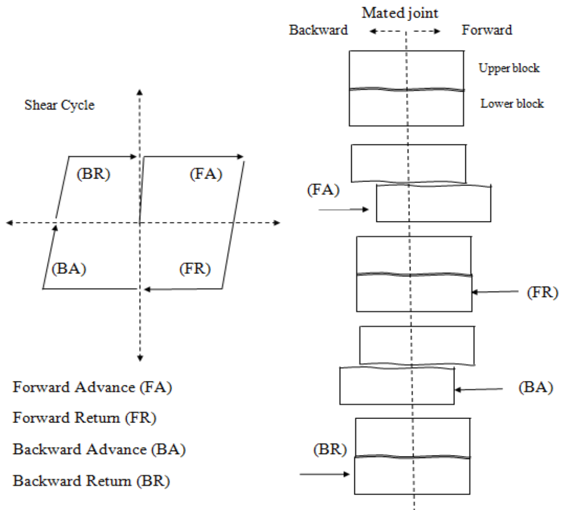

Figure 1: Load direction and joint movement under shear cyclic condition.

2. SAMPLE PREPARATION

Similar sample preparation methodology is adopted for preparing both regular and irregular joints, except for the use of different asperity plates to create different asperity angles. A model material is found in such a way that it can easily be handled and reproducibility of the sample can be ensured. To achieve this, different brands of plaster of Paris and dental plasters at different moisture content and curing period in isolation or combinations were assessed. Finally, plaster of Paris (POP) was selected because of its universal availability and its ability to mould into any shape when mixed with water to produce the desired joints, as well as its long term strength being independent of time once the chemical hydration is completed. The prescribed percentage of water was decided so as to achieve proper workability of the paste and required strength to simulate the soft rock. Different water POP ratios were tried in order to obtain desired strength and workability. The ratio which was finally selected was 0.60. Size of samples and amplitude of asperities are 298×298×125 mm and 5 mm respectively for all of the joints based on moulds and asperity plates. The asperity plates of different angles like 15°-15° and 30°-30° and 15°-30° and 15°-45° were designed and fabricated to produce desired asperities in the sample. The POP with 60% of the moisture was mixed in the mixing tank for 2 minutes and then the material was poured in the casting mould which was placed on the vibrating table as presented in Figure 2. Vibrations were given to the sample for a period of 1 minute to remove any entrapped air. The sample was demoulded from the mould after 45 minutes and kept for air curing for 14 days before testing. Pre-test regular and irregular joints are shown in Figures 3 and 4, respectively. The uniaxial compressive strength of model material at 0.60 water cement (POP) ratio and after 14 days of air curing was 6 MPa.

3. LARGE-SCALE DIRECT SHEAR APPARATUES

A servo controlled large-scale direct shear system designed by Shrivastava and Rao (2012) was modified to be able to carry out tests under cyclic shear conditions. This system is illustrated in Figure 5, which consists of three main units, namely the 1) loading unit, 2) data acquisition with controlling unit and, 3) hydraulic power pack. Maximum capacity of the normal and horizontal load cell was 500 KN and 1000 KN, respectively. The size of each shear box was 300 mm × 300 mm × 448 mm. This system can work under both static and cyclic condition.

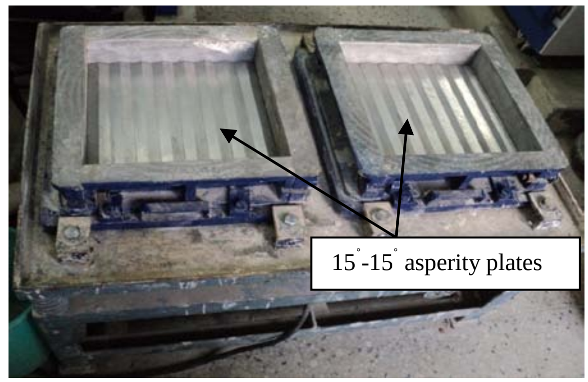

Figure 2: Set up for sample preparation.

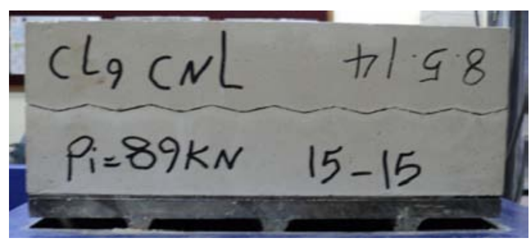

Figure 3: Regular joint (15°-15° asperity angle).

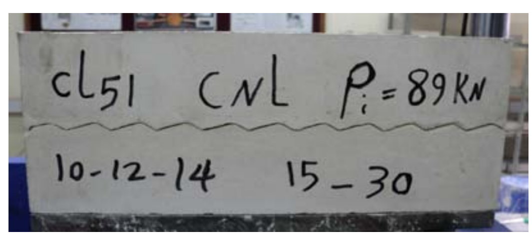

Figure 4: Irregular joint (15°-30° asperity angles).

4. EXPERIMENTATION

The cyclic shear tests were conducted on regular and irregular joints under different normal stresses. Normal stresses are 0.1 MPa and 1 MPa as low and high, respectively. The frequency and amplitude of shear loads are set to constant values of 0.01 HZ and +-8 mm, respectively for all cyclic shear tests. Each type of specimen is tested on thirty shear cycles under constant normal load conditions. The orientation of samples with irregular joints is important when loaded because of the different asperity angles. Experimental results are plotted, first and last shear cycles are shown in black and red colors in the graphs and from 2-29 shear cycles are presented in blue color for clarity.

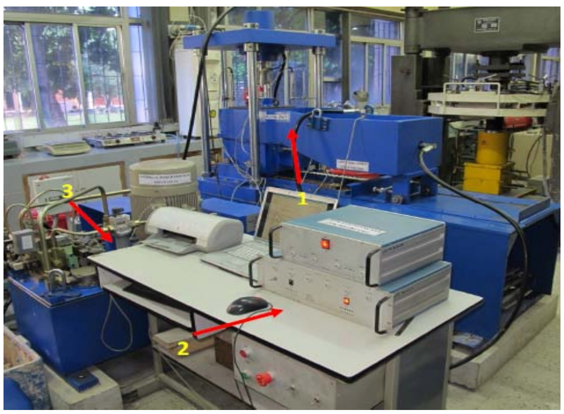

Figure 5: Large scale direct shear testing machine.

4.1 Low normal stress (P=0.1 MPa)

Shear stress versus horizontal displacement on the joints with asperity angles (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45° at P=0.1MPa are presented in Figure 6. Figure 6 (a) indicates that no significant change is observed on the peak shear stress from first to last (30) shear cycles on the joint with 15°-15° asperity angle, whereas it decreases with increasing number of shear cycles for 30°-30° asperity angle, as shown in Figure 6 (b). The peak shear stress at initial cycles for the joint with 30°-30° asperity angle is more than for the 15°-15° asperity angle, but it decreases for 30°-30° asperity angle and the peak shear stress is less than for the 15°-15° asperity angle after several shear cycles, i.e. peak shear stress on joint with 30°-30° asperity angle is less than 15°-15° asperity angle at 30 shear cycles. Normal displacement versus horizontal displacement on the joints with asperity angles (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45° at P=0.1 MPa is presented in Figure 7. The dilation angle for 15°-15° asperity angle is constant during 30 shear cycles as shown in Figure 7(a), but it decreases by increasing the number of shear cycles for 30°-30° asperity angle and dilation on the joint after several shear cycles is converted to compression (positive normal displacement) as indicated in Figure 7 (b). Mechanism of the shear is changed from sliding on the low asperity angle (15°-15°) to shearing on the joint with the high asperity angle (30°-30°) at the same normal stress under cyclic shear loads.

Irregular joint shear behaviour is significantly different from that of the regular joint. Shear strength of the irregular joint as indicated in Figure 6(c) is more than that of the regular joint as presented in Figure 6(b) on the same slope of asperities at different cycles of shearing. With increasing irregularities (the difference of angles between two slopes of asperities is increased) or the joint with 15°-45° asperity angle, the peak shear stress is increased. However, it rapidly decreases with increasing number of shear cycles, as shown in Figure 6(d). No significant change is observed on peak shear stress on the lower slope of asperities or backward movements. Figures 7(c) and (d) reflect that dilation and dilation angle is more on the higher slope of asperities and decreases gradually until it is equal with the lower slope of asperities. However, dilation and dilation angle of the regular joints both are constant or decrease gradually and equally on forward and backward movements from first to last shear cycles, as indicated in Figures 7(a) and (b). Irregular joints have a tendency to convert to regular joints at low normal stress under cyclic shear loads. Degradation of irregular joints is more predominat on the slopes at higher angles rather than at lower angles on the asperities.

4.2 High normal stress (P=1 MPa)

Shear stress versus horizontal displacement on the joints with asperity angles (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45° at P=1MPa is presented in Figure 8. Normal displacement versus horizontal displacement of the same joints at P=1MPa is indicated in Figure 9. The peak shear stress increases with the increasing normal stress for all types of joints. In addition, the peak shear stress increases with the increasing asperity angle and irregularity of the joint at first shear cycle (in forward advance). After two or three shear cycles, all types of joints reach relatively the same shear stress level and behaviour of the joints changes from non planar to planar, due to the complete shearing of asperities of the joint at high normal stress. This joint behaviour or transition from nonplanar to planar becomes more obvious as the normal stress on the joint under cyclic loads increases. With increasing normal stress, compression is created on the joints. Small dilation is observed on regular joints only at first cycle at high normal stress, as presented in Figures 9(a) and (b).

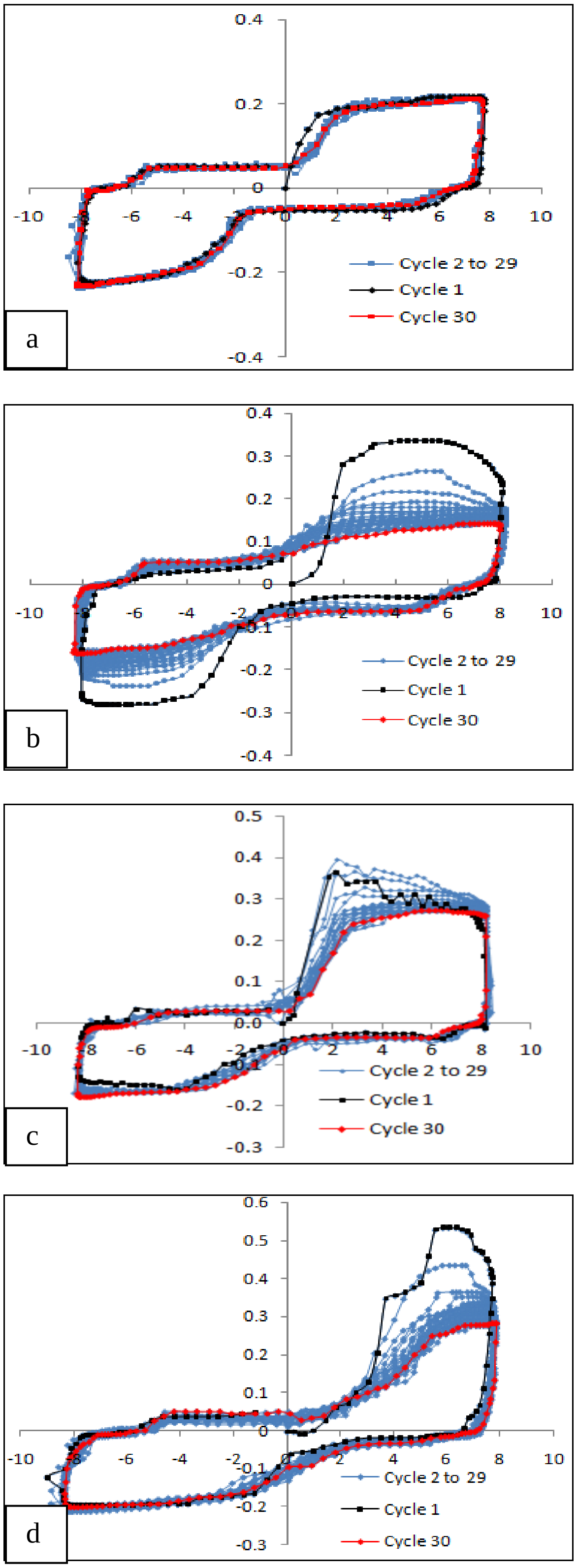

Figure 6 : Shear stress versus horizontal displacement on the joints with asperity angles, (a) 15°-15°, (b) 30°-30° (c) 15°-30° and (d) 15°-45° at P=0.1 MPa.

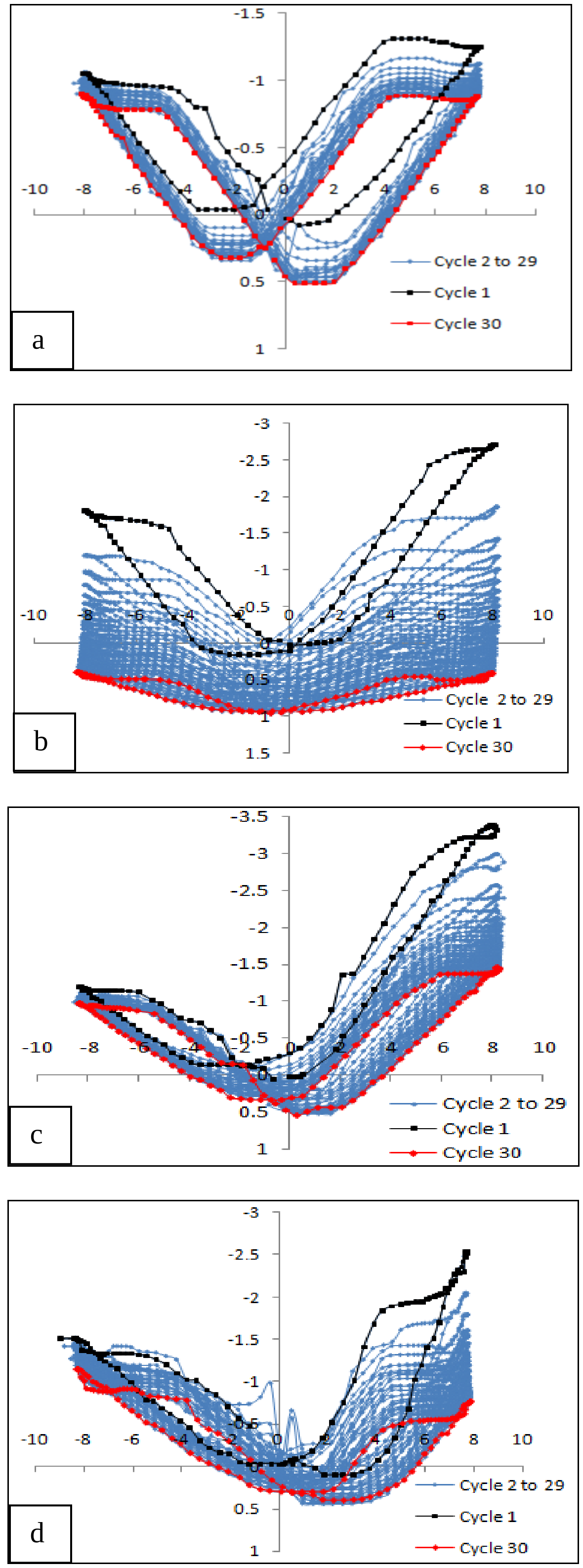

Figure 7: Normal displacement versus horizontal displacement on the joints with asperity angles, (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45at P=0.1 MPa.

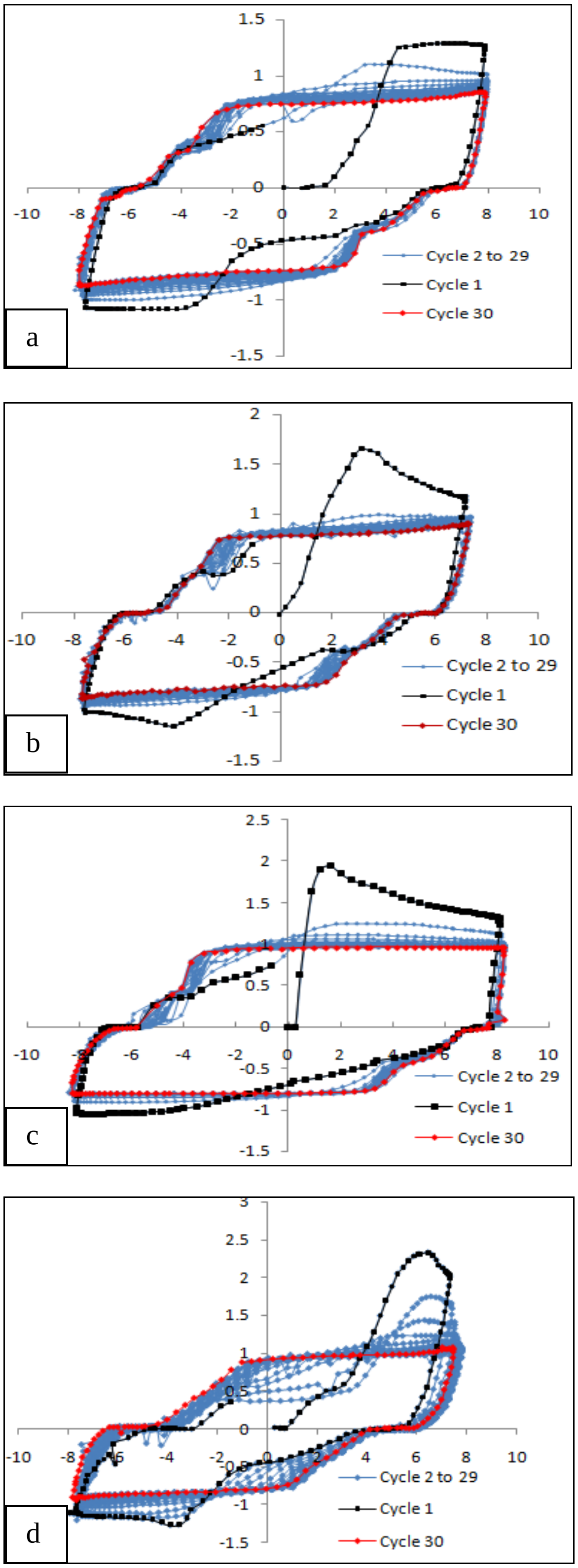

Figure 8 : Shear stress versus horizontal displacement on the joints with asperity angles, (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45 at P=1 MPa.

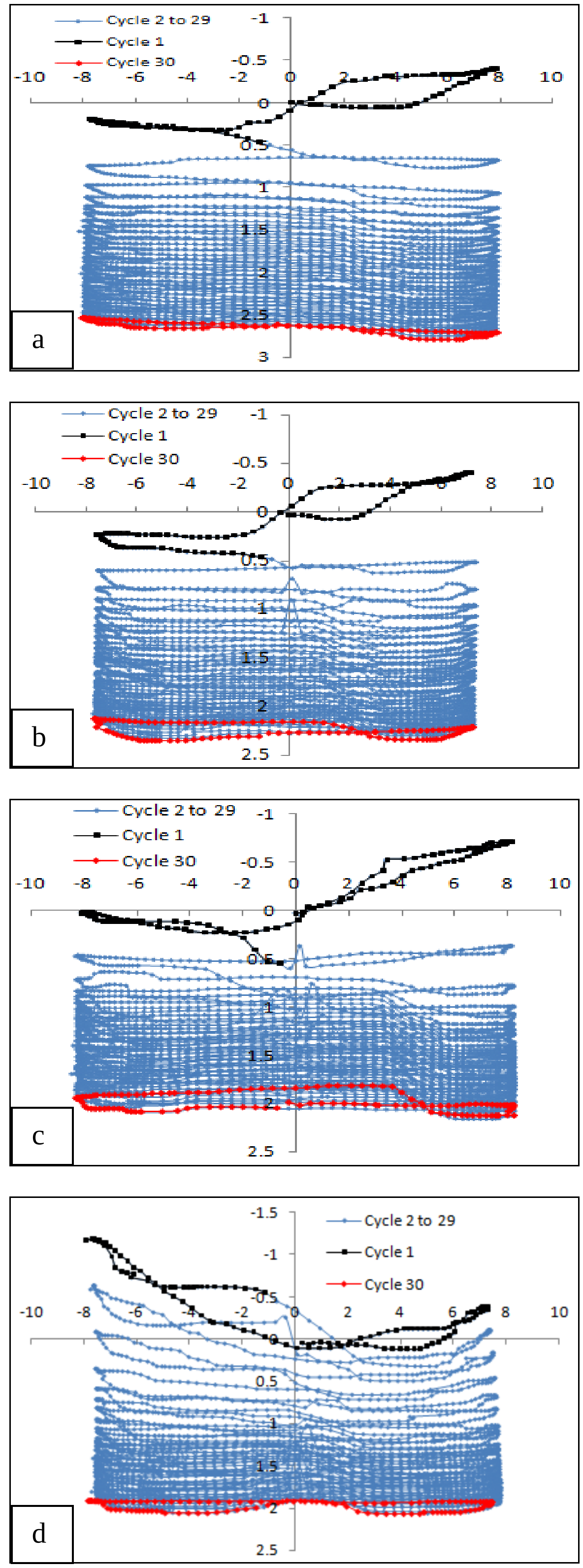

Figure 9 : Normal displacement versus horizontal displacement on the joints with asperity angles, (a) 15°-15°, (b) 30°-30°, (c) 15°-30° and (d) 15°-45 at P=1 MPa.

In the case of irregular joints, dilation and dilation angles start to increase in the backward movement with increasing irregularities as shown in Figure 9 (d). Dilation and dilation angles on the slope of asperities with lower angles increases in backward movement with respect to the other joints, and it is either due to increase in slope angle because of deformation on another part of slope in first movement, or some debris getting deposited on this slope due to first shearing and joint degradation on the slope of asperity with higher angle. Horizontal displacement corresponding to peak shear stress decreases with increase in asperity angle, whereas it increases with the increasing irregularity of the joint.

5. CONCLUSION

The test results indicate that the shear strength of rock joints increases with increase in asperity angles and normal loads at first cycle of shearing. With the increase in the number of shear cycles, the shear strength reduces for all the asperity angles (except a joint with a low asperity angle at low normal stress). However, the rate of reduction is greater in the case of asperities with higher angles. Natural rock joints are irregular, but most prior studies have been conducted on regular joints. In the present study, cyclic shear tests were performed on both regular and irregular joints for comparison. Shear strength of irregular joints was found to be higher than that of regular joints at different cycles of shearing at low normal stress. The analysis of design of structure on rocks by using the above test results makes the design safer and more economical. The mechanism of shearing for regular and irregular joints is different under cyclic conditions. Shear strength and degradation of asperities on the regular joints between loading and unloading are the same at low normal stress, whereas for irregular joints they are different. Shear strength and joint degradation are more on the slope of asperity with higher angles on the irregular joints, untill two angles of asperities become equal under shear cycles at low normal stress when it starts behaving like the regular joints.

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