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Laboratory Assessment for Frictional and Joint Deformation Properties of Rock

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Abstract. This paper describes about laboratory assessment of frictional and joint stiffness parameters of slate and quartzite rocks obtained from Himalayan region, under constant normal load (CNL) condition. The investigation was carried out using laboratory direct shear test apparatus both on tight and open jointed samples. The estimated values of cohesion and friction angles at peak and residual shear stress were compared for both jointed rocks. It is observed that the frictional parameters of open jointed quartzite rocks have resulted in lower values than tight jointed slate rocks. An attempt was also made to estimate normal stiffness and shear stiffness of these jointed rocks. Irrespective of rock type and nature of joint, non-linear behaviour witnessed through stiffness data invariably. On comparison, the tight jointed slate rocks gave much higher values of stiffnesses than the open jointed quartzite rocks. As applied normal stress increases, the slope of the shear stress versus shear displacement of open jointed rocks changes from smooth to rough.

Keywords: direct shear test; frictional parameter; joint characteristics; joint normal stiffness; joint shear stiffness

1. Introduction

In the design of civil structures lying in and on rock, it is very much essential to understand the behaviour of joints or discontinuities, which play significant role in assessing the behaviour of rock masses especially for excavations, slopes, and underground openings. The parameters that majorly affect the strength of joints are cohesion, angle of internal friction and stiffness [1,2]. Moreover, the numerical studies for any complex engineering problems, these as input parameters have paramount importance in assessing the influence of discontinuities in blocky rock masses. Hence, it becomes crucial that rock joints properties are adequately determined before any engineering construction decisions in and on rocks. The actual shear strength estimation of rock mass can be possible through in-situ direct shear test. Since the method is time consuming and expensive, the laboratory estimation of shear strength is generally adopted for small-scale rock materials which gives good estimation for preliminary judgment of shear strength of rock mass. Researchers advise to exercise caution in application of these laboratory shear parameters in the analysis of landslides as the later covers dynamic events, in such situations, site-specific studies are mostly preferable.

To estimate the basic shear parameters (cohesion, c and angle of internal friction, Φ) and stiffness of joints in laboratory, a direct shear test is usually performed on rock cores or rock blocks under a constant normal load applying directly on the discontinuity plane [4]. The procedure for obtaining c and Φ both at peak and residual stress states through the laboratory direct shear test is well illustrated in the literature [10]. The discontinuities sometimes may be open or almost closed (tight joints). Shear strength of a joint can be assessed under Constant Normal Load (CNL) or under Constant Normal Stiffness (CNS) conditions. The CNS condition [5] is preferably used for assessing shear strength in sliding rock blocks, where normal stress is continuously changing. The CNL test does not really provide shear strength of joint rather provide shear resistance at a defined normal load. However, CNL condition is considered to be appropriate for the usage of parameters in design with some boundary conditions. In CNL condition, constant normal loads of various magnitudes applied on samples and respective shear and normal displacements (at given shear rate) recorded to determine the shear stresses. Minimum three to five specimens with similar characteristics from same test horizon must be selected for testing [10].

The normal stiffness and shear stiffness are two such deformational parameters of joint, estimates of which are very much needed in limit equilibrium analysis of rock in underground or surface constructions [7, 11]. The ratio of normal stress and shear stress to the respective normal and shear deformation are defined as joint normal stiffness (K_n) and joint shear stiffness (K_s). However, the estimation of these parameters under laboratory conditions is a challenging task [8].

The first use of joint normal stiffness term was by Goodman [3] to describe finite joint element in rock block. Since then, it's an essential factor for assessing mechanical behaviour of joints in numerical models. Several researchers [6, 8, 9] have clearly shown that K_n significantly vary with applied normal load. Theoretically, at a constant normal stress, joint normal deformation is measured by subtracting deformation of intact rock from deformation of a single jointed rock. Malama and Kulatilake [6, 8] showed that how the normal deformation – normal stress relation is obtained by performing a uniaxial test on sample having a horizontal joint. An attempt has been made to assess joint normal stiffness by applying incremental normal loads adopting the above illustrated procedure [8] in the present study. And, the joint shear stiffness is measured by elastic region curve slope of shear stress v/s shear displacement plot.

In present paper, frictional parameters (cohesion and internal friction angle); and, normal and shear stiffness of jointed Quartzite (open jointed) and Slate (tight or almost closed jointed) rocks from Himalayan region have been assessed using the established procedures [8, 10] available in the literature. The direct shear test apparatus available at CSMRS' laboratory (Make: Robertson Research International Limited) is used for conducting shear strength tests on rock cores (54mm diameter) under constant normal load (CNL) condition.

2. Experimental Work

For carrying out direct shear test experiment, the rock core specimens of 24 numbers each, from Quartzite (tight/almost closed joints), and Slate (open jointed) rock, with length to diameter ratio of 2.0, were prepared as per ISRM suggested method [10]. The selected specimens are encapsulated in casting material (prepared using 1:3 Cement Mortar mix) by maintaining proper fit and alignment of jointed plane to the shear plane. Also, it was ensured that the test zone is not contaminated with encapsulating material. After initial hardening, the encapsulated specimens were soaked in water for 28 days before undergoing direct shear test.

The direct shear tests were carried out on multiple samples of Quartzite and Slate rocks at constant normal stresses ranging from 1-8MPa, to ensure closure of the joints. The soaked encapsulated rock core specimens were then mounted and oriented in a shear box of Direct Shear test. The shear box apparatus made by Robertson Research International Ltd. was used for conducting shear tests. To induce normal and shear load, two manually operated hydraulic pumps of 50 kN capacity are provided and stresses were measured with accuracy +/- 2% using pressure gauges. To measure normal displacement and shear displacement vertical and lateral dial gauges (0.002mm L.C.) were used during the test. One dial gauge attached parallel to shear plane for measuring shear displacement and another dial gauge placed vertical to measure normal displacement.

The encapsulated specimens mounted in the shear box were tested under different normal loads. The normal load applied till the specified normal stress with a gradual rate on encapsulated specimen, and consequently the normal displacements measured. The applied constant normal load was maintained on the mounted encapsulated specimen for the entire duration of the shear test. After stabilization of normal load, the shear load with a gradual rate of displacement was applied.

At least 10 readings of applied shear stress along with shear displacements were recorded at these intervals before reaching the peak shear strength. The recorded values were then used for plotting the respective shear stress v/s shear displacement, and normal stress v/s normal displacement graphs. Joint shear stiffness is measured through shear stress v/s shear displacement curve slope in the elastic region.

2.1 Joint Normal Stiffness

In normal stress versus normal displacement plot, first non-linear portion formed due to joint closure is considered for estimation of joint normal stiffness. For subtracting the linear part, a parallel line was drawn to the linear portion through the origin, which provides a theoretical linear part of the intact rock displacement.

3. Results and Discussion

The results of investigation for assessment of shear behaviour of discontinuity plane and for estimation of joint normal stiffness and joint shear stiffness are discussed in relevant sections. Figure 1 shows the selected specimen photographs of Quartzite and Slate rock in direct shear test.

Using the recorded data, the shear stress versus normal stress at peak and residual, for all specimens are plotted. The shear strength parameters are evaluated using Mohr-Coulomb criteria. In the sense of Mohr-Coulomb's failure theory, the apparent cohesion (c) and the friction angle (φ) are defined as follows:

$$\tau = c + \sigma \tan \varphi$$

where,

'φ' = arctangent ratio of peak shear load to the corresponding normal load,

'φ_{res}' = arctangent ratio of residual shear load to the corresponding normal load,
Residual shear load = When the specimen reaches a large shear displacement at similar shear load without any increase.

'c' = intercept of the peak strength envelop on the shear stress axis, and

'c_{res}' = intercept of the residual strength envelop on the shear stress axis.

3.1 Shear Behaviour of Joints

Table1 shows the calculated friction angles and cohesion values. Peak internal friction angle value of 34° and peak cohesion value of 2.0, are observed in tight jointed slate rock, when sheared apart along discontinuities. In tight jointed rocks, due to the bond in-between the two interfaces of upper and lower part of rock, a significant difference observed between the peak and residual shear strength values and internal angles of friction. The increase in peak shear strength with the increase of normal stress shows that there is a pronounced effect of asperities and interaction area, at each increment of normal stress during the test.

(a)

(b)

Fig. 1. Selected samples of (a) Open jointed Quartzite rock, (b) Tight jointed Slate rock

For open jointed discontinuities of quartzite rock, the shear strength parameters are much lower than that of tight jointed rock, due to the very little cohesion in open joints. Owing to this reason, the difference between the peak and residual internal friction angle values for open jointed rock is only 2° and observed almost similar cohesion values at peak and residual stages.

Table 1. Shear Strength Parameters and Stiffness of Joints.

Parameter	**Tight Jointed Rock (Slate)**	**Open Jointed Rock (Quartzite)**
Cohesion - Peak, c (MPa)	2.0	1.1
Internal Friction Angle - Peak, φ (Degree)	34	24
Cohesion - Residual, c_{res} (MPa)	0.9	0.9
Internal Friction Angle - Residual, φ_{res} (Degree)	26	22
Joint Normal Stiffness –k_n (MPa/mm)	5.1	4.0
Joint Shear Stiffness – k_s (MPa/mm)	3.2	0.7

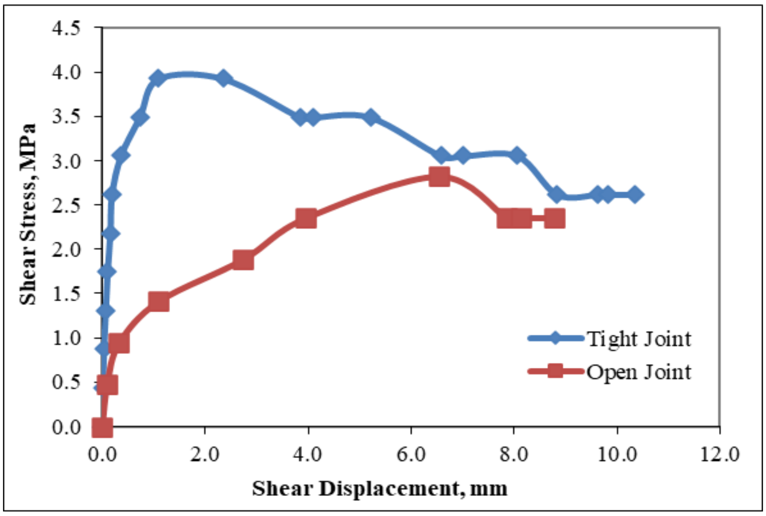


Fig. 2. Typical shear stress versus shear displacement graph for tight and open jointed rocks

At low normal stresses, it is observed that the shear behavioral characteristics of tight and open jointed rocks were significantly differ from each other (Fig. 2), whereas at relatively increasing normal stresses the shear behaviour of both rock joints were found to be broadly similar. This indicated that surface morphology is showing superseding effect on contact area and textural interlocking at low normal stress than at relatively higher normal stresses. This could be possible due to damage and smoothening of asperities during shear movement at relatively higher normal stress. Similar types of curve patterns are observed in other specimens also.

On comparing the results of tight and open jointed specimens (Fig. 3), the slopes of trend lines clearly represent the behavior of tested shear surfaces. The high angle of friction was measured in tight joint rocks in comparison to open jointed rocks. The residual values are much closer to peak values in open jointed rocks and on increasing the normal stress their difference also increases. These lower values clearly indicate the inherent variations of slate and quartzite rocks and the nature of the discontinuity.

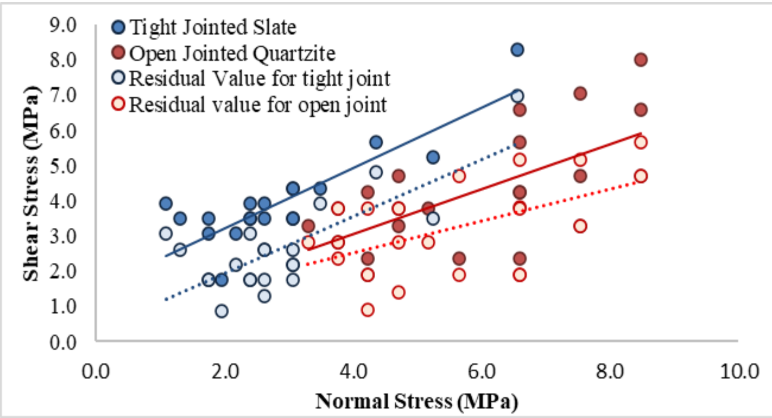
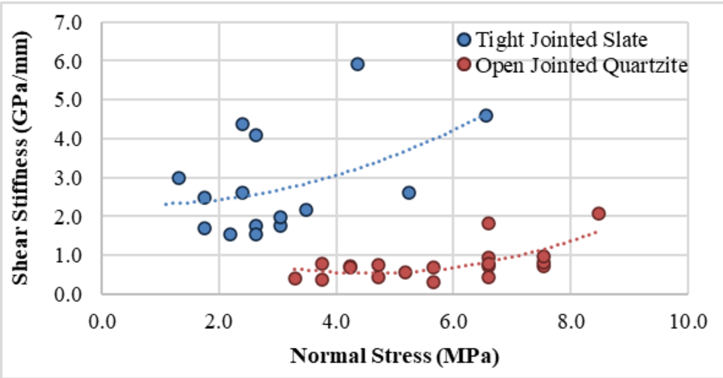


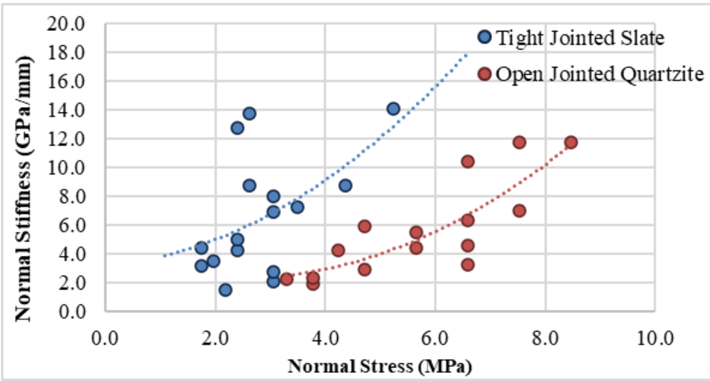
Fig.3. Comparison for shear behaviors of tight and open jointed rocks

3.2 Normal stiffness (k_n) and Shear stiffness (k_s) of joints

An attempt has been made to estimate the normal stiffness and shear stiffness of Joint through direct shear tests. Total 24 samples of each from tight and open jointed rock variants were tested at different normal stresses and corresponding displacements were measured through dial gauges. The data shows normal stiffness of joints is considerably more than shear stiffness (Fig. 4).



(a)

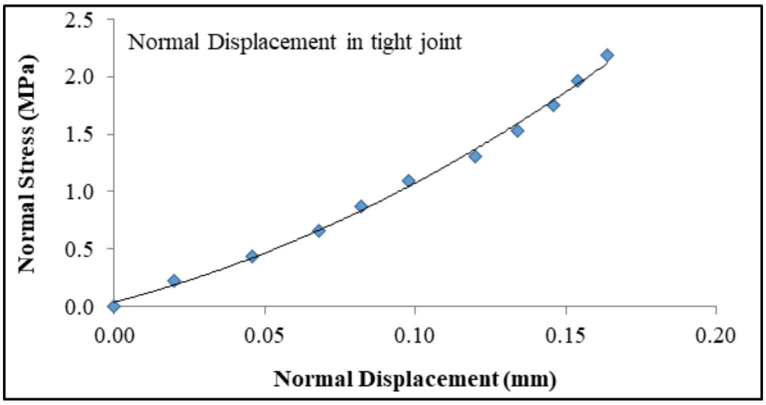


(b)

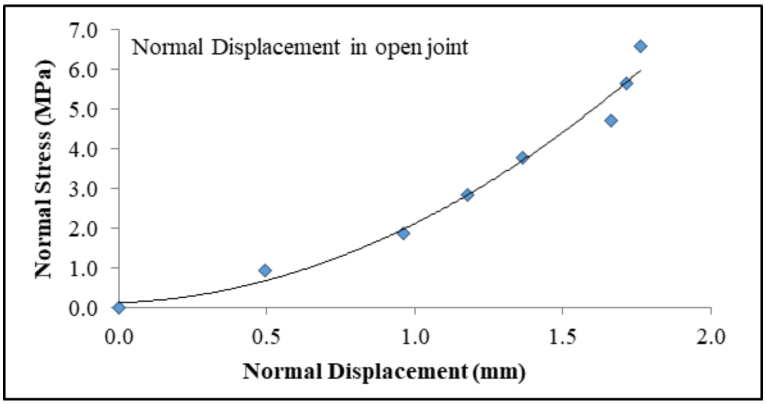
Fig. 4. Comparison for, **a)** normal stress versus shear stiffness, **b)** normal stress versus normal stiffness of joints

The deformation of the open jointed rock dominated by joint interface displacements. In tight jointed rocks the slope of the curves becomes steeper with increasing normal load, considering that the joints have reached up to its closed state and any additional normal load will be taken up by the solid rock only. The evaluated stiffness values are presented in Table 1.

Joint Normal Stiffness (k_n). Before initiating the shear test, the joints were normally loaded and the normal stiffness (k_n) was estimated for each normal stress, as per procedure illustrated in literature [10]. The normal stiffness (k_n) of tight joints found to be about 2GPa/m to 8GPa/m at normal stress ranging from 1MPa to 6MPa. Whereas the normal stiffness (k_n) of open joints was found to be about 1GPa/m to 5GPa/m at normal stress ranging from 3MPa to 8MPa. Both joint, have shown non-linear behaviour under normal loading (Fig.5). An exception here is, in the case of extremely tight jointed slates, almost linear behaviour has exhibited under normal load.



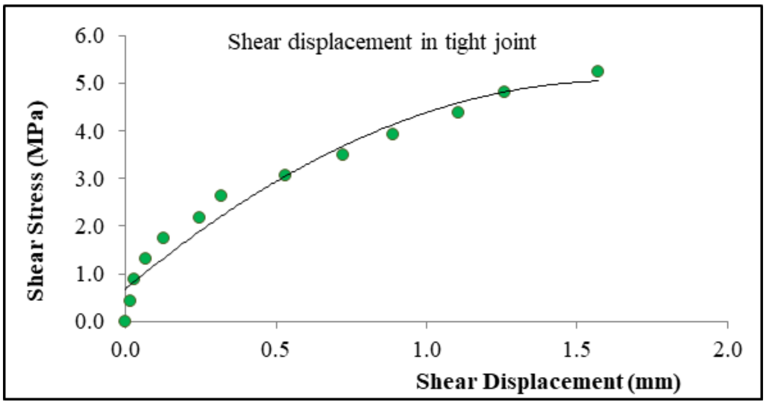
(a)



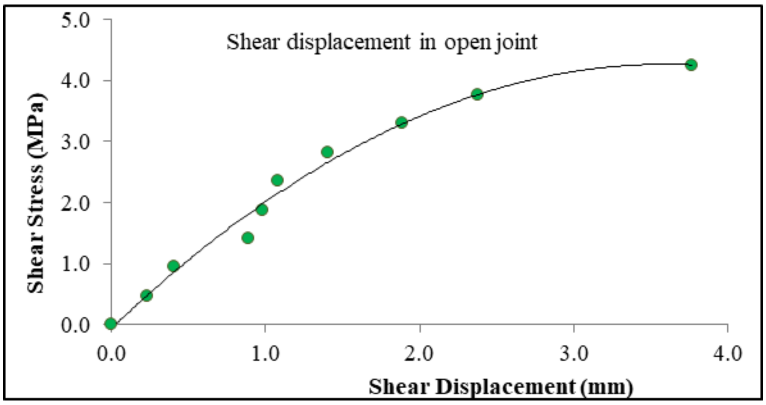
(b)

Fig. 5. Typical normal displacement curve for, a) tight joint, b) open jointed rocks

Joint Shear Stiffness (k_s). Shear deformation up to the peak shear strength was measured for the selected rock samples. Generally, the shear stiffness is estimated from slope of linear portion of shear stress v/s shear displacement plot. However, in present case due to non-linear behaviour, stiffness is estimated by drawing tangent at 50% of stress, for both joint rocks. The shear stiffness (k_s) of tight joints was found to be about 4GPa/m to 6GPa/m at normal stress ranging from 1MPa to 6MPa. Whereas, the shear stiffness (k_s) of open jointed rock was found to be about 0.3GPa/m to 2GPa/m at normal stress ranging from 3MPa to 8MPa. Depending on normal stress, peak shear stiffness (ks) of open jointed quartzite rock specimens was 3 times lower than that of tight jointed slate rock specimens. The displacement curve of the specimens showed non-linear behaviour as shown in Fig.6.



(a)



(b)

Fig. 6. Typical shear displacement curve for, a) tight joint, b) open jointed rocks

4. Conclusions

In the present study, shear behaviour of open jointed quartzites and tight jointed slates obtained from Himalayan region, is assessed through shear parameters (cohesion, internal friction angle, both at peak and residual stages). For this, laboratory direct shear test has been conducted on rock cores. Also, an attempt has been made to estimate normal stiffness and shear stiffness of these jointed rocks. Based on results, it is inferred that,

(1) The joint closure varies non-linearly with normal stress and irrespective of the rock and joint type. Under increasing normal stress, the joints gradually reach a state of maximum closure, whose value is directly dependent upon the preceding stress history.

(2) The shear stress-shear deformation relations reveal non-linear behaviour of joints in pre-peak range. Non-linearity is more profound in cases of opened joint and least in tightly interlocked joints. The stress-strain behaviour of a tight joint and open jointed rock extensively depends on the state of stress and anisotropy.

(3) At low normal stresses, shear behaviour of tight jointed and opened jointed rocks were significantly differ from each other, whereas, at relatively increasing normal

stresses, the shear behaviour of these joints was found to be broadly similar. It is realised that friction instantly comes into effect, which take over the bond strength at high normal stresses.

(4) The stiffness values are fairly high for tested interfaces. The shear stiffness (k_s) is significant because it is essentially the stiffness of the bond between the interfaces.

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