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Effect of Joint Roughness on the Compressive Strength of Singly-jointed Rock

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ABSTRACT: Cylindrical cement-mortar specimens 84 mm in diameter and 168 mm in height were prepared. Water-jet cutting was used to create a single joint for each specimen on a plane inclined at 40° to the minor principal stress direction. Standard profiles defined by set ranges for Joint Roughness Coefficient (JRC) value were used to produce a jointed sample set with varying roughness. Five different JRC values were considered, to cover the whole range of the JRC scale (i.e. 2-4, 6-8, 10-12, 14-16 and 18-20). Two identical sample sets (one dry and one fully water-saturated) were tested under uniaxial compression. For high values of JRC, lower UCS was observed for the fully-saturated samples when compared to the dry samples. The difference in results between the dry and fully-saturated tests may be related to effective stress phenomenon, or may relate to lubrication of the joint surface in the case of the fully-saturated samples.

1 INTRODUCTION

The presence of discontinuities (joints) within a rock mass decreases its overall strength and can influence its deformation and permeability characteristics. The strength of rockis strongly influenced by the geometrical properties of joints, including length, orientation relative to principal load, surface roughness, etc. This paper addresses the influence of one of the many geometrical properties of joints – joint surface roughness – on unconfined compressive strength of rock-like brittle materials.

Joint surface roughness has been quantified using many different descriptions. Often, the amplitude of surface asperities is used as the principal variable for description of joint surface roughness. The Joint Roughness Coefficient (JRC), an arbitrary variable defined by Barton (1973), is one of the most popular definitions for joint surface roughness.The standards of international society for rock mechanics (ISRM) recommend the use of the JRC as a measure of joint surface roughness for civil and mining engineering applications.

1.1 *A review of existing knowledge*

1.1.1 *Theoretical knowledge*

Mohr-Coulomb theory can be applied to describe the shear strength of rock joints but does not specifically consider the influence of joint surface roughness on the shear strength of rock joints. An early attempt to account for the influence of joint surface roughness on the Mohr-Coulomb failure criterion for joint surfaces was presented by Patton (1966), and is summarized in Equation 1:

$$\tau = \sigma_n' \times \tan(\emptyset_b + i) \quad (1)$$

where, τ is the joint shear strength, σ_n' is the effective normal stress, $\emptyset_b$ is the basic friction angle of the joint surface and i is the initial asperity angle of the undulations.

Later, an empirical criterion that considered a more detailed arbitrary description for joint surface roughness – the JRC – was introduced by Barton (1973) (Equation 2). Equation 2 is often referred to as Barton's failure criterion.

$$\tau = \sigma_n tan\left[JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right) + \emptyset_b\right] \quad (2)$$

where, σ_n is the normal stress, JCS is the joint wall compressive strength and JRC is an empirical variable relating to joint surface roughness. The different arbitrary JRC profiles defined by Barton (1973) are shown in Figure 1.

Taking the weathering of rock joints in to consideration, Barton and Choubey (1977) presented a slightly different version of Barton's failure criterion, after testing on 130 variably weathered rock joints. This revised version of the failure criterion is given in Equation 3:

$$\tau = \sigma_n tan\left[JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right) + \emptyset_r\right] \quad (3)$$

where$\emptyset_r$is the residual friction angle, which is calculated by Equation 4:

$$\emptyset_r = (\emptyset_b - 20) + 20(\tfrac{r}{R}) \quad (4)$$

where$r$ is the Schmidt rebound number for wet, weathered fractures and R is the Schmidt rebound number on dry, unweathered, sawn surfaces.

Many modified versions of the Barton's failure criterion of Equation 2 have been proposed, with consideration of various different applications involving engineering of jointed rock. The interested reader is referred to the studies of Kulatilake et al. (1995), Indraratna et al. (2008) and Grasselli and Egger (2003).

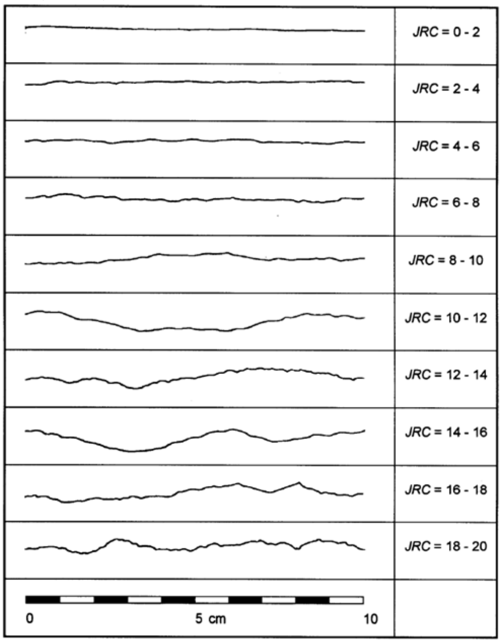

Fig. 1 Joint Roughness Coefficient profiles, as defined by Barton (1973)

1.1.2 *Experimental outcomes*

Jiang et al. (2006) carried out direct shear tests on artificial joints for three different JRC values, and one natural rock joint, which was estimated to have a JRC value of 0-2. The artificial joint generation techniques used by Jiang et al. (2006) were not explained in their manuscript. Sinha and Singh (2000) tested artificial regular shape rock joints filled with gouge using a triaxial compressive strength testing approach. Both undulating and planar joint surfaces were used in the testing of Sinha and Singh (2000), but exact JRC profiles (as defined by Barton 1973) were not produced and JRC values for the joints were not given. Indraratna et al. (2008) conducted triaxial compressive strength tests on specimens with clay-infilled joints. Saw-toothed joint surfaces, with alternating angles of 60° from the planar average surface were created using gypsum plaster and a prefabricated cast. Wong and Chau (1998) performed uniaxial compressive strength tests on sandstone-like material containing non-persistent artificial joints (cracks) produced by embedding then removing a perfectly planar metal razor. Naghadehi et al. (2010) tested natural rock samples containing natural joints with different roughness. Both direct shear and tilt tests were conducted on dry and saturated jointed specimens, in order to investigate the influence of moisture on jointed rock behavior. Kulatilake et al., (1995) developed new peak shear strength criteria for jointed rocks by direct shear testing on jointed rock models cast from a mixture of plaster of Paris, sand and water. Their joint profiles were chosen to simulate the actual topographic features of natural joints, recorded using silicone rubber casts. A series of direct shear tests were conducted by Shigui et al. (2011) on natural rock joints, under both dry and saturated conditions. The surface roughness were correlated to JRC for each natural joint by statistical means. Gu et al. (2003) tested jointed rock models produced from a sand-cement mixture by direct shear methods. They used water-jet cutting to produce artificial joint surfaces (both regular and irregular surfaces). However, they did not attempt to replicate the original JRC profiles of Barton (1973). From the above review of experimental studies related to joint roughness, some important research gaps are apparent.

- The vast majority of experimental studies that have considered the roughness of rock joints were performed under dry conditions, and the effect of saturation on the influence of roughness on joint shear strength has not been thoroughly investigated.
- Many of the studies considered saw-toothed (regular) and/or arbitrarily irregular joints roughness patterns and accurate replication of original JRC profiles in terms of both the undulations and length of the joint has not been attempted.

An experimental study was designed to directly address the above-mentioned knowledge gaps, using an innovative specimen production methodology that utilizes high-precision water-jet cutting. We report on the results of the experimental work below.

2 EXPERIMENTAL METHODOLOGY

2.1 *Sample preparation*

A model material made from cement mortar was used for all tests. Ordinary Portland Cement was mixed with glass-grade sand and water at the ratio of 1:3:0.7 by volume, respectively, to make cement-mortar blocks. The blocks were cured inside a curing room for 28 days, before cylindrical specimens with a diameter of 84 mm were cored from them. Following curing, the individual cores were cut using a diamond saw to produce cylindrical specimens 168 mm in height. The mix proportions, and casting and curing processes were carefully controlled during sample preparation to ensure the physical properties of the cement-mortar specimens were reproducible.

2.2 *Joint generation*

The experimental program utilized specimens containing fully-cut joints, inclined to the loading direction. In choosing the inclination angle for the joints, we considered two factors: (1) the most favorable joint orientation to ensure failure will occur along the pre-existing joint and not through the intact material (for the JRC values used), and (2) the use of joints with the exact length of the JRC profiles defined by Barton (1973) – i.e. 100 mm. With consideration of the above points, a 40° joint inclination value (as measured from a direction perpendicular to the loading direction) was selected.

The artificial joints with five different JRC values (2-4, 6-8, 10-12, 14-16 and 18-20) were created by water-jet cutting. The water-jet cutting approach uses a high-pressure water jet that follows a computer-programmed profile. This is a simple but precise technique that can be used for exact replication of desired joint profiles. Following cutting, the joint surfaces were examined using a profilometer, to ensure the precision of the method. The method displayed a remarkable level of accuracy when compared with the original JRC profiles. The generated JRC profiles for the five different values are shown in Figure 2 (Figure 2 shows only one of the two complementary halves that remained after water-jet cutting for each specimen).

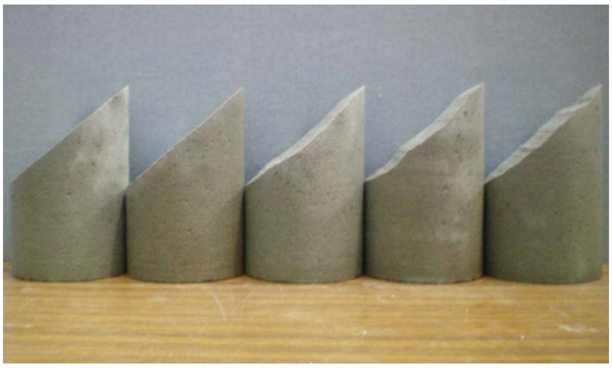

Fig. 2 Samples with different Joint Roughness Coefficient values, after water-jet cutting (from left to right, JRC = 2-4, 6-8, 10-12, 14-16, 18-20)

No joint infill material was used for the experimental specimens. Two identical specimen sets were prepared. One set was placed in a water bath until the specimens became fully water saturated (full saturation was ensured by periodic weight measurements of the specimens until three subsequent measurements were identical). The remaining set was heated in a drying oven at 60 °C for four hours and then kept in dry storage prior to testing.

2.3 *Testing procedure*

Constant-strain Uniaxial Compressive Strength (UCS) testing was carried out on each specimen by following the specifications outlined in the ASTM standards (ASTM 2000). Saturated specimens were tested immediately after being removed from the water bath in which they were kept, to ensure that moisture loss prior to testing was minimized.

3 RESULTS AND DISCUSSION

The UCS values obtained from the testing, for both dry and saturated specimens are shown in Table 1.

Table 1. UCS values for dry and saturated specimens

JRC	UCS	
	Dry	Saturated
2-4	0.165651	0
6-8	1.804478	1.082687
10-12	1.984926	2.129284
14-16	2.938412	2.165373
18- 20	4.511195	2.526269

The variation of UCS against different JRC for both dry and saturated specimens is shown in Figure 3.

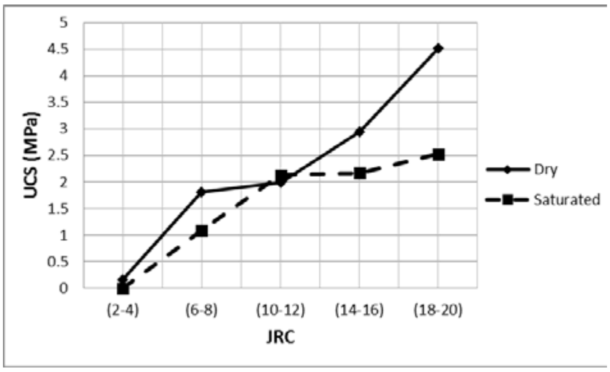

Fig. 3 Unconfined Compressive Strength v. Joint Roughness Coefficient (JRC)

The experimental work of Naghadehi et al. (2010) and Shigui et al. (2011), carried out on natural joints in natural rock samples, demonstrated a dependence between joint shear strength and moisture content, whereby saturated specimens showed lower strength. Figure 3 demonstrates a similar scenario. From Figure 3, it is clear that UCS is higher for dry samples than for saturated samples for values of JRC of 14 to 20. Uncertainties associated with the limited testing data make it difficult to resolve such differences for lower values of JRC (Figure 3). It is apparent that saturation-related weakening in our testing is more prominent for rougher joints than for smoother joints. This behavior may be related to effective stress phenomena, lubrication phenomena, or a combination of these. More work will be required to probe the exact physical origin of the saturation-related weakening with increasing JRC.

The failure patterns of specimens were also of interest, as the testing program was designed with the assumption that failure would occur exclusively by sliding along the pre-existing joint. Table 2 shows the observed failure patterns for all specimens.

Table 2. Failure patterns for all Uniaxial Compressive Strength specimens

JRC	2-4	6-8	10-12	14-16	18-20
Dry					
Saturated					

According to Table 2 it is clear that failure occurred by sliding on the pre-existing joint for all JRC values and saturation conditions considered. However, for the highest JRC values used, some small fractures were observed to have developed within the intact material. This was most obvious for the dry specimens. Such additional cracking may have been avoided by the use of a slightly steeper joint inclination than 40°. However, for compliance with the original JRC profile length (i.e. 100mm), the specimen diameter would have to be smaller than the 84 mm value used here to allow for the larger inclination value.

This paper presents results of only one test at each JRC value and for a more complete data set more tests are needed. Additionally, the experimental work considers cement-mortar specimens with unfilled, water-cut synthetic joints. The experimental results are specific to the methodology and specimen type utilized and the authors suggest researchers are cautious with general application of the results of this study to engineering problems involving different rock types and joint scenarios. Nevertheless, this study provides an initial foray in to the topic of the influence of saturation on the strength effect of joint roughness, and introduces a novel methodology for accurate reproduction of rock joint geometries, using high-precision water-jet cutting techniques.

4 CONCLUSIONS

An experimental study was carried out to quantitatively determine the effect of joint roughness on compressive strength of rock. Water-jet cutting was used to accurately embed a single artificial joint that followed a pre-defined joint surface profile in specimens made from cement mortar. Joint surfaces with JRC values of 2-4, 6-8, 10-12, 14-16 and 18-20 were used for each sample set. UCS tests were performed on both dry and saturated jointed specimens. All samples displayed failure by sliding along the pre-existing artificial joint surface. The testing results showed that no resolvable difference in UCS between the dry and saturated samples was observed for low values of JRC (with consideration of the uncertainty associated with the limited number of test samples). However, the experimental results showed a significant weakening effect with saturation for values of JRC of 14-16 and 18-20 (i.e. rough joints). More work is required to investigate the origin of the saturation weakening effect for the shear strength of rough joints and whether such an effect is resolvable for smoother joint profiles.

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