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# The influence of asperity deformability on the mechanical behavior of rock joints

Khabat Amiri Hossaini, Nima Babanouri, Saeed Karimi Nasab*

*Department of Mining Engineering, Shahid Bahonar University of Kerman, Kerman 76196-37147, Iran*

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ABSTRACT

The main purpose of this study is to investigate the effect of deformability of joint material on the deformability of rock joints. To do this, replicas of natural rock joint surfaces were constructed using plaster and concrete materials with different values of Young's modulus. The replicas underwent direct shear tests with various values of normal stress. The results of 110 direct shear tests show that the deformability of asperities considerably affects normal and shear behaviors of joints. For joints with equal wall compressive strength values, those having higher deformability show higher shear strength. This is due to the fact that higher deformability of asperities results in increasing the contact area during shearing. Based on statistical analyses of the experimental results, the Young's modulus of joint material was incorporated into the Barton–Bandis empirical relationships in order to better estimate the peak shear strength, shear stiffness, rate of dilation, and the shear displacement corresponding to the peak.

## 1. Introduction

Fractures can significantly affect the mechanical behavior of rock systems, especially in the vicinity of the ground surface where the stress level is low. The deformability behavior of a rock mass is mainly controlled by the joints as their number increases. Hence, the factors controlling the behavior of rock joints under different stress fields must be identified and incorporated into an appropriate constitutive model to describe the mechanical behavior of discontinuous rock media [1]. Rock joints may be divided into two groups: in-filled joints and clean joints. The shear behavior of in-filled rock joints mostly depends on physical and mechanical characteristics of the filling material and its thickness [2].

The mechanical behavior of clean joints depends on different factors such as surface roughness, joint wall compressive strength (*JCS*), normal stress ($\sigma_n$) [3,4], shear rate [5], joint surface matching [6,7], aperture [8], boundary conditions of the shearing process (including constant normal load (CNL) and constant normal stiffness (CNS)) [9], over-consolidation effect [10], weathering [11], and scale effect [12,13]. Various shear failure criteria and constitutive models have been developed. Shear failure criteria presented by many researchers such as Patton [14], Ladanyi and Archambault [15] and Barton [3,4] are only used for estimating the peak shear strength. In order to describe the whole shearing process (including hardening and softening behaviors), different constitutive models such as the Amadei–Saeb theoretical model [1] and the Barton–Bandis empirical model [1] have been developed. Since the shear behavior of rock joints is very complicated and influenced by many parameters, each model and criterion is able to account for only a limited number of the parameters. Among the existing models, the Barton–Bandis constitutive model provides the most realistic representation of the various aspects of rock joints behavior observed in laboratory experiments, especially non-linear normal and shear behavior, dynamic behavior under cyclic normal and shear loadings, asperity degradation during shear displacements, and the effect of scale [1].

Nevertheless, the impact of deformability properties of joint material on the normal and shear behaviors of rock joints has been neglected, and only the strength and frictional characteristics of the joint material have been considered in the existing constitutive models. In other words, the models proposed for the shear behavior of rock joints have been established based on the two mechanisms of shearing and sliding of surface asperities. However, elastic/inelastic deformations of the joint materials play an important role in the joint shear behavior [9]. Johnston and Lam developed a series of analytical expressions to describe the shear behavior of regular triangular concrete/rock joints. The analytical relationships better correlated with the experimental results when the asperities were assumed to be compressible rather than rigid [16,17]. Seidel and Haberfield studied the shear behavior of fractured or plastically deformed joints under CNS conditions [18]. They proposed a theoretical model to predict the shear behavior of soft rock joints. This model included micro-mechanical simulation of joint shearing under CNS conditions [18]. Based on the results of direct shear tests

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* Corresponding author. Tel.: +98 341 2112764; fax: +98 341 2121003.
*E-mail address:* kariminasab@uk.ac.ir (S. Karimi Nasab).

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on rock joints, Roko et al. stated that to properly understand the shear behavior of rock joints, the initial geometry of the joint surface is not adequate to be considered and the asperity deformation is also necessary to be taken into account [19]. Indraratna et al. introduced a method to account for the change in normal stress and surface degradation during CNS shearing [9,20]. However, almost no effort has been made to incorporate deformability properties of rock material, specifically Young's modulus ($E$), into models and criteria presented for the mechanical behavior of rock joints. Moreover, in the few studies conducted on the deformability behavior of joint asperities, triangular asperities have been mostly used for simplicity. Nevertheless, the mechanical behavior of rock joints with a complex natural roughness could be very different from the behavior of joints with tooth-shaped asperities. A set of systematic tests is needed to understand and quantify the impact of deformability of asperities on both normal and shear behaviors of rock joints.

In this study, the effect of deformability properties of joint material on the shear behavior of rock joints has been investigated through physical modeling and laboratory mechanical experiments. Plaster and concrete replicas of natural rock joints with different deformability and strength properties were prepared and subjected to normal and shear loads. The direct shear tests were conducted under a wide range of surface roughness and normal load values. Application of the two types of material (i.e. plaster and concrete) for joint replicas provided a direct observation of the influence of the deformability of asperities on the joint shear behavior. The results of the tests were statistically analyzed in order to determine the role of Young's modulus of joint material in the constitutive equations of rock joints.

## 2. Preparation of samples

To avoid the effect of individual difference in the morphological properties of fractures (e.g. roughness and aperture) on the normal/shearing process with different deformability properties, several replicas were prepared from natural rock joints. To ensure that the deformability properties of the replicas are significantly different, they were produced using different plaster and concrete materials.

### 2.1. Modeling the joint surface roughness

Four natural joints with different degrees of surface roughness were selected as the parent joints. The natural rock joints were taken from the Gol-e-Gohar iron ore mine (Iran), and silicon molds of them were prepared. The profiles of the natural joint surfaces were mapped by a contact method using a profile comb. The preliminary estimation of the joint roughness coefficient (*JRC*) values was made by visual comparison of the captured profiles and the ten standard profiles presented by Barton and Choubey [21]. In order to obtain coefficient values of joint surface roughness more accurately, three profiles along the shearing direction from all the parent surfaces were digitized. Then, using the relationship between *JRC* and the statistical parameter $Z_2$ (root mean square of the profile's first derivatives), presented by Tse and Cruden [22], the accurate *JRC* values of the parent joints were estimated equal to 18.87, 12.43, 7.10, and 4.12 (Fig. 1).

To obtain mated replicas of natural rock joints, the upper (or lower) surface of the natural joint was first molded and constructed using a silicon mold with plaster or concrete. Then, the other surface of the joint replica was molded and superimposed on the first surface. All the samples were formed cylindrically with a diameter of 60 mm. Upper and lower surfaces of plaster joint replicas were painted with red color so that even a small degree of damage during the shearing process could be easily observed.

### 2.2. Plaster replicas

For each parent joint, a number of fracture replicas were produced using a high-strength plaster material with the commercial name of Crystacal D which mostly consists of $CaSO_4$, $1/2H_2O$ components. This plaster is suitable for preparing detailed hard replicas [23].

Table 1 shows mechanical properties of the prepared plaster samples with three different ratios of plaster to water (*P/W*). This information was obtained from the uniaxial compressive strength ($\sigma_c$) and Brazilian tests on the unjointed cylindrical plaster specimens which were prepared under the same conditions as the joint replicas were cured (i.e. preserving in a desiccator for seven days). The basic friction angle of $34^\circ \pm 1.56^\circ$ was measured for different *P/W* ratios using the tilt test.

**Table 1**
Mechanical properties of plaster samples with different ratios of *P/W*.

| Material no. | Plaster/ water ratio (*P/W*) | Young's modulus (GPa) | Uniaxial compressive strength (MPa) | Tension strength (MPa) | Density (g/cm3) |
|---|---|---|---|---|---|
| 1 | 4 | $11.36 \pm 0.02$ | $52.12 \pm 2.14$ | $4.23 \pm 0.34$ | 1.89 |
| 2 | 3 | $8.66 \pm 0.45$ | $41.59 \pm 1.18$ | $3.18 \pm 0.41$ | 1.64 |
| 3 | 2 | $3.83 \pm 1.24$ | $17.24 \pm 3.78$ | $2.81 \pm 0.24$ | 1.31 |

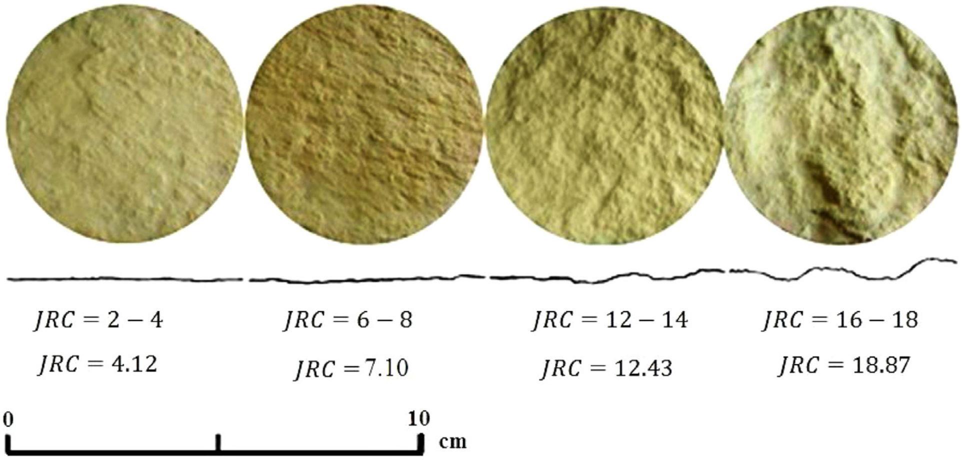

**Fig. 1.** Plaster joint replicas with four different degrees of roughness along with the *JRC* values obtained from both the visual comparison and the statistical relationship.