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Investigation of Shear Properties of Open Non-persistent Latitudinal Discontinuities of Same Level

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Abstract

In this paper, the effect of variations in the number and area of the rock bridges on the non-persistent discontinuities is investigated. In this regard, blocks containing rock bridges and joints with dimensions of 15 cm * 15 cm * 15 cm are prepared from plaster. The available rock bridges that have occupied 0.2, 0.4, and 0.6 of the shear surface show latitudinal extension along the shear surface. There are variations in the number and extension of the rock bridges in the fixed area. For each of the samples, tests are performed on three blocks of the same material, by putting it under various direct normal stresses. Normal stresses were 3.33, 5.55, 7.77 kg/cm2. Also the obtained shear strength by laboratory tests was compared with the outputs of Jenning's criterion and Guo and Qi's criterion to determine the accuracy of these criteria for predicting the shear strength of non-persistent joints. The results show that the tensile crack started in the rock bridge under normal stress of 3.33 kg/cm2. Mixed-mode tensile shear cracks were propagated in the rock bridge under a normal stress of 5.55 kg/cm2, while a pure shear crack developed in the rock bridge under a normal stress of 7.77 kg/cm2. With the increase of normal stress, the number of microfractures increased. The variance in the number of rock bridges in the fixed area of the rock bridge does not affect the friction angle along the shear surface. Furthermore, the cohesion along the shear surface shows a small decrease with the increasing number of rock bridges. Also by the increase in the area of rock bridges, the friction angle along the shear surface remains constant, while at the same time, there is an almost linear increase in cohesion. Guo and Qi's criterion predicts the shear strength of the non-persistent joint exactly close to the shear strength of the physical samples.

1. Introduction

From various points of view, the rock discontinuities have an important role in the rock failure mechanism. The presence of rock joints, especially in some sections of the rock mass, causes a reduction in the rock resistance [1]. In some cases, it is possible to limit the failures in the rock structures with some specific discontinuities. It is usually several discontinuities in various sizes that results in a combined shear surface [1]. In this sense, the neighboring discontinuities that make up the rocky part of the rock mass are called rock bridges, with the greatest impact on the shear resistance of the rock joint face [2, 3]. Because the precise measure and position of the rock bridges in the rock mass is difficult to determine, thus it is not of considerable importance in the in the mechanical rock designs. The main reason that the rock bridges are a resistive factor to the crack is that before the crack is to take place along the weak surface, initially these segments have to be broken, and the resulting cracks have to propagate to the surrounding rock joints [4]. The coalescence of cracks in natural rock masses are experimentally studied by conducting some special laboratory tests

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on real rock (or prepared rock-like) specimens with multiple cracks. These tests provide significant results related to the crack propagation mechanisms of pre-existing cracks including the primary (wing) and secondary (shear) cracks usually originating from the crack tips [5]. The primary and secondary cracks originating from the tips of one original crack may propagate and coalesce with one another or they may extent to coalesce with the other cracks in the neighborhood, specially when multiple pre-existing cracks or joints are present in the specimen. However, extensive works (uniaxial [6-8], biaxial [9-12], and triaxial [13-15] compression tests) have been carried out in relatively recent years to study the failure and fracture mechanisms of brittle rock specimens containing multiple cracks. The effects of rock bridges in between the pre-existing (filled or unfilled) joints of a rock mass on the mechanical behavior and failure mechanism of natural rocks are studied by many researchers [16-20]. The initiation and propagation of tensile (primary) and shear (secondary) cracks from the original cracks and joints may reduce the tensile and shear strengths of rock massed in slopes and underground spaces [21]. The yield pillars in the potash mines of Saskatchewan subjected to collapse due to non-persistent tensile and shear cracks arrays developed during the failure of the rock structure [22]. Some *in-situ* tests conducted by Li *et al.* [23] using the borehole camera for monitoring the convergence in deeply buried tunnels. It was observed that the convergences of the surrounding rock occurred due to extensions and coalescences of the joints already existing in the rock mass in form of a microfracture zone around the hole. The pre-existing rock joints may produce a step-path failure mechanism in a typical rock slope as observed experimentally by Huang et al [24]. Many laboratory tests were carried out focusing on the effects of the geometry and arrangement of non-persistence joints on the shear strength of the rock masses. The shear tests carried out by Salvilahti *et al*. [25] on cast plaster samples (contained nine different patterns of joints and rock bridges) revealed that when multi-joints are present in the samples, the non-overlapping joints extend and coalesce one another in mixed (tensile and shear) modes. The rock bridges separated these joints in both vertical and horizontal directions, while the overlapping joints mainly propagated and coalesced in tensile mode. The failure mechanism of rock-like material samples with arrays of open joints studied by Wong *et al*. [9] explained the effects of joint separation on the shear strength of rock masses. Zhang *et al*. [26] also investigated the effects of joints' geometry on the failure mechanism of rocks considering the rock bridges. Ghazvinian *et al*. [17] considered the effects of rock bridges in rock-like material specimens three-dimensionally. Their analyses revealed that the persistency of rock bridges may control the mechanism of failure and fracture in rocks. Other researchers worked on non-persistent and en-echelon joints in rock samples, and showed the effects of joints and joints' geometry on the failure mechanism and shear strength of rocks under various loading environments [25]. They suggested three different phases of failure for en-echelon joints i.e., tensile splitting, joint sliding (due to fillings) and dilatant expanding due to friction. Gerolymatou and Triantafyllidis [26] studied the shear failure of non-persistent joints considering the joints' geometry (orientations) and fracture mechanics' principles. Recently more attentions are devoted to the effects of joint's roughness and joint's filling on the shear resistance of the jointed rock masses [27-37]. Effects of joint's roughness on the shear behavior of non-persistent rock joints were studied by Asadzadeh *et al*. [27] who considered the coefficient of joint roughness for the joints' asperities. The joint roughness condition (JRC) at different levels (low, medium and high) were considered for the cracks initiated from the joints' asperities under different normal and shear stresses. The effects of normal stress and joints' persistency on the failure mechanism of granite specimens were studied by Yang [38]. Three modes of failure (i.e. tensile, shear, and compressive failures) were observed experimentally.

In most of previous research works, the effects of intermittent joints on the failure parameters (cohesion and friction angle) of rock specimens with non-persistent joints were ignored. However, in this research work, the rock bridges and their strength parameters (cohesion and friction angle) are taken into account in the analyses. The cohesion and friction angle of rocks may change considering the, number and extension (area) of rock bridges in a particular rock mass. The joints and the bridges in between are prepared in rock blocks, and the direct shear tests are carried out. The joints are open, and the shear characteristics of joints may not affect the shear strength of the block. The experimental shear strength tests carried out in laboratory and the shear strength of non-persistent joints determined. The Jennings and Guo and Qi criteria were used to verify the accuracy of the results [39, 40].

2. Preparing Samples and Testing Program

2.1. Mixing material

The samples are prepared by mixing water and plaster in the proportions of 1.5/1= chalk/water. The plaster can be considered as a material with the same characteristics as rock, and because of the advantages of 1, the possibility of collecting many samples 2, the possibility of repeating the results.

2.2. Stainless steel mold preparation

After mixing water and plaster, the mixture in poured into an especial mold that is made up of two separate sections, connected together by the related screws (Figure 1). In the upper section of one of the molds, two sheets separate from each other with the width of one centimeter and the length of 17 cm is installed in such a way that by putting them along side each other, a crack is created. In the ongoing discussion, the usage of the above sheets will be discussed. In order to create rock joints and rock bridges in the sample, aluminum blades are used that are cut to shape for use (Figure 2).

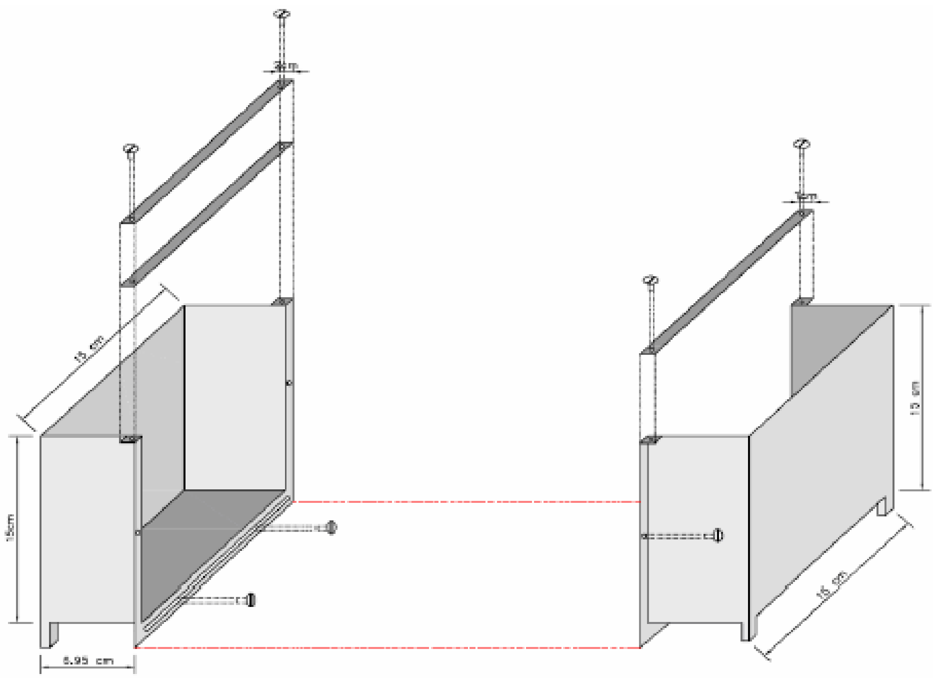


Figure 1. Mold used for building the samples.

The various shapes of the blades are necessary in order to make the creation of the semi-continuous rock bridges a possibility (Figure 2). Also the blades with the thickness of 1 mm and length of 20 cm having various widths are bent exactly 2 cm from the upper section. The placement of the blades in the mold is in such a way that after dipping it in the grease, the bent section is inserted into the crack that was created by the two sheets, and the sheet present in the other mold keeps the original sheets stationary by applying pressure on the blades. Also the lower section of the blades is placed between the two molds and hence prevents their movement.

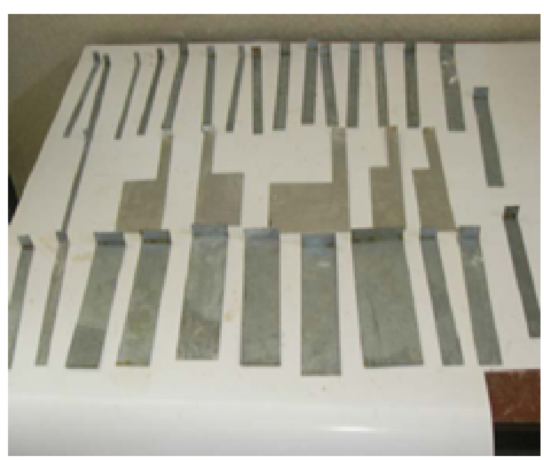


Figure 2. Sheets used in order to create joints in the rock bridge.

2.3. Preparation of sample containing non-persistent joins

After placing the two sheets in the mold, the vibration is started at the same time that the mixture is poured into the mold. After about 1 hour, the samples are separated from the mold, and blades are removed form the sample. The mixture is prevented from sticking onto the blades by applying the grease, thus making the removal process simple. It does not seem that removing the blades, damages the crack in any way. In this way, each blade leaves a joint with the thickness of 1 mm.

2.4. Rock bridges with different geometry

The rock bridges occupy an area of 0.2, 0.4, 0.6 of the shear surface (Figure 3).

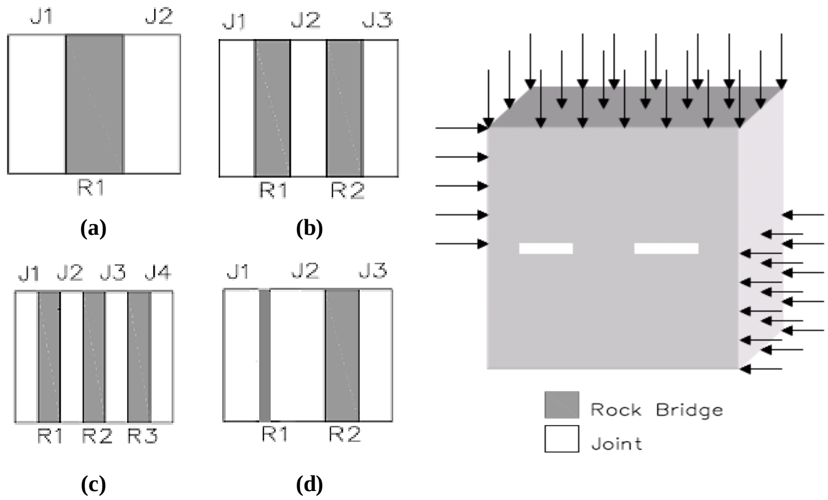


Figure 3. Various rock bridge samples created for the test.

These are expanded latitudinal along the width of the shear surface. Their number varies within a fixed area between 1 to 3. By combining the characteristics of each rock bridge, it is possible to explain its especial geometry. For example (P, 2, (0.066, 0.13) is related to the geometry of a rock bridge that is persistent and are two in number. Each rock bridge occupies 0.13, 0.066 of the shear surface (Figure 2a, 2b, 2c, 2d). In Table 1, it is possible to see the characteristics of all the rock bridges.

In all, 36 samples that consist of 12 types of rock bridges were prepared. In order to measure the conhesion (c_{RB}) and the friction angle (φ_{RB}) along the shear surface of each sample, three blocks were prepared. Furthermore, three intact blocks containing no rock joint or rock bridge were also prepared for measurement of c_i and φ_i.

Table 1. Characteristics of tested rock bridges.

P, 1, .2	P, 2, (.2, .2)	P, 2, (.66, .533)
P, 1, .4	P, 2, (.3, .3)	P, 3, (.066, .066, .066)
P, 1, .6	P, 2, (.066, .133)	P, 3, (.133, .133, .133)
P, 2, (.1, .1)	P, 2, (.066, .33)	P, 3, (.2, .2, .2)

It is also necessary to mention that in order to make sure of the similarity between resistance characteristics of the combination, from each block two cylindrical samples with the thickness of 5.7 cm and height of 11.4 cm for the uniaxial test were prepared. The samples were kept for 4 days in the laboratory temperature. At the end of this period, the uniaxial test was performed on the seeds and the blocks were placed under direct shear test.

2.5. Testing program

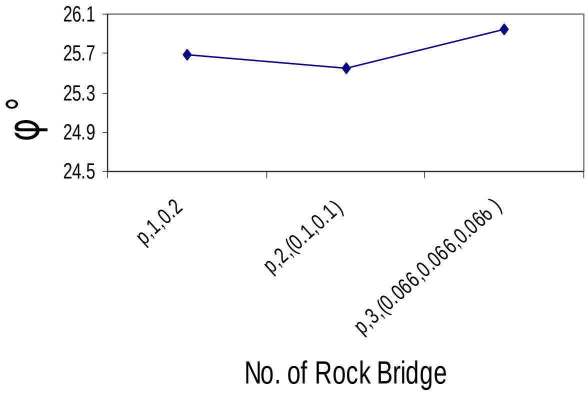
The test was performed using the direct shear equipment of 50 KN. All the samples containing similar rock bridges, were put under three normal stresses of 3.33, 5.55, 7.77 (σn) kg/cm^2. The test is performed in such a way that the sample is subjected to the normal stress (σn), and then the shear stress (τ) is applied up to the break point.

During the test, the amount of shear movement is measured by LVDT, while applied loads are measured by the load cell. In the end, the curve $\tau - \sigma_n$ was sketched, and the amounts of c and φ for each state were calculated. It is also necessary to mention that during the test, the samples without surface crack are removed and other samples are used instead.

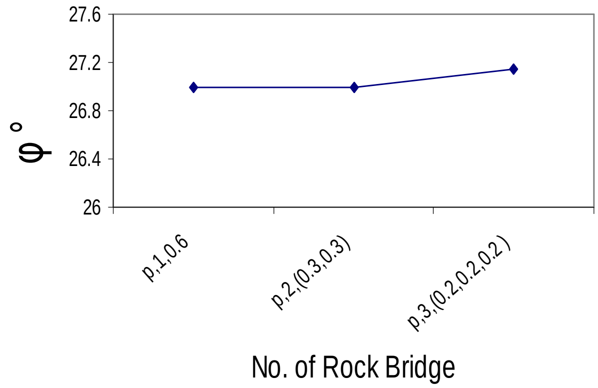
3. Experimental Results

3.1. Effect of increase in number of continuous rock bridges in fixed area of the rock, on shear properties along crack surface

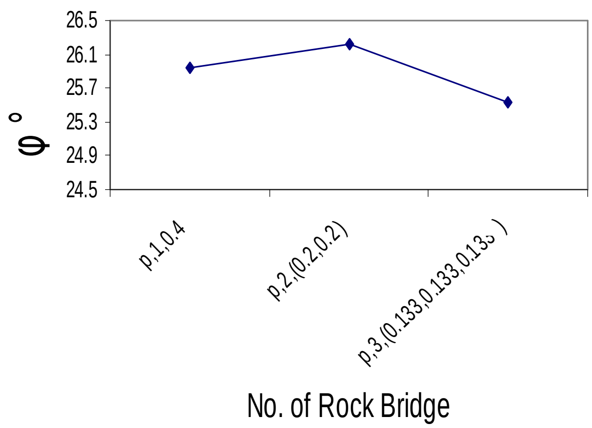
The variance in the shear resistance (τ) along the crack surface based on the increase in the number of rock bridges (in the fixed area of the rock bridge) is shown in the Figures (4.a, 4.b, 4.c). This Figure for the normalized areas of 0.2, 0.4, 0.6 is divided in three sections of a, b, and c. (normalized area = area of rock bridge (A)/total area of the shear surface (A`)). As it is observed, the fixed normalized area, with the increase in the number of rock bridges, the friction angle along the shear surface shows a considerable increase.



(a)



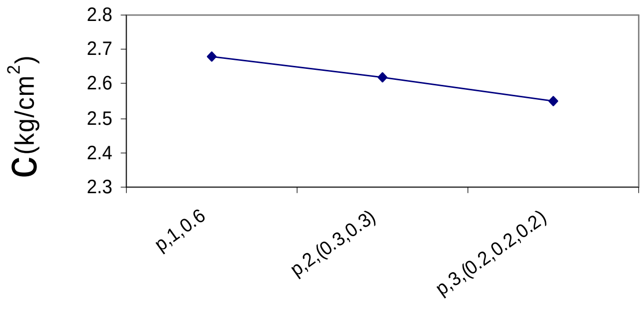
(b)



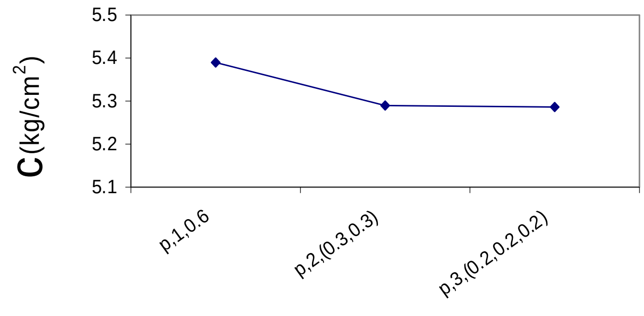
(c)

Figure 4. Change in the friction angle along the shear surface based on the increase in the number of rock ridges in the fixed area of the rock bridge; a. normalized area of 0.2, b. normalized area of 0.4, c. normalized area of 0.6.

The variance in cohesion along the shear surface based on the number of rock bridges, in the fixed area of the rock bridge is shown in Figures (5a, 5b, 5c). The rock bridges with the normalized areas of 0.2, 0.4, 0.6 are divided into three sections labeled a, b, and c.



(a)



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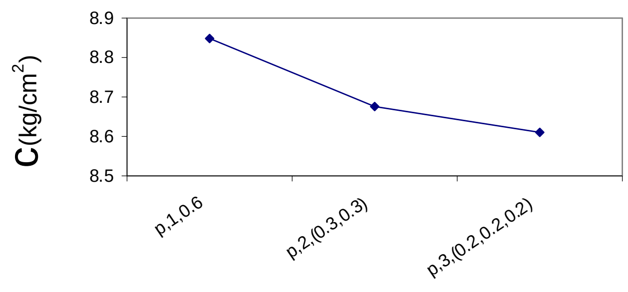


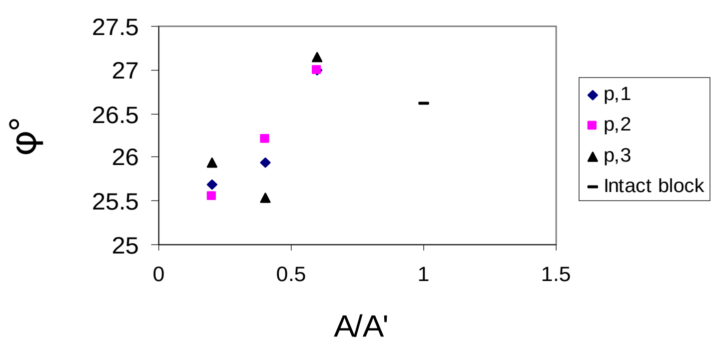
(c)

Figure 5. Variance in the cohesion along the shear surface, based on the increase in number of rock bridges in the fixed area; a: normalized area of 0.2; b: normalized area of 0.4; c: normalized area of 0.6 .

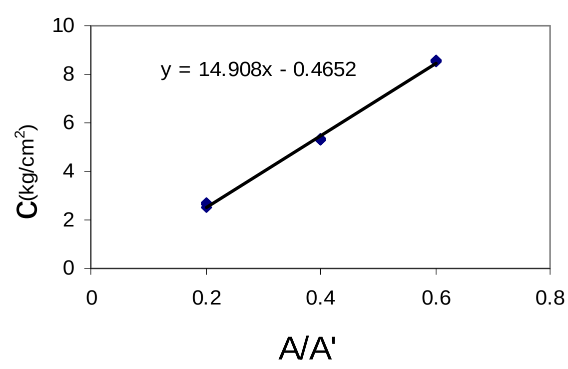
As it is observed, with the increase in the number of rock bridges in the fixed area of the rock bridge, the cohesion along the shear surface show a small decrease, and the reason for that is the increase in number of weak points in the shear path due to the increase in number of rock bridges. But due to the fact that the increase in number of rock bridges in the fixed area of the rock bridge has the effect of decreasing the cohesion with a small amount, hence it is possible to ignore that effect.

3.2. Effect of increase in area of persistent rock bridges to shear characteristics along shear surface

In Figure 6a, the variance in the friction angle along the shear surface based on the increase in normalized area of the rock bridge is shown. In Figure 6, the internal friction angle of the intact mass is also included.



(a)



(b)

Figure 6. (a) Changes in the internal friction angle based in the increase in normalized area of the rock bridges; (b) variance in cohesion based on the increase in the normalized area of the rock bridges.

As it is observed, by the increase in the normalized area of the rock bridges, the friction angle shows a considerable variance along the shear surface, which is nearly equal to the internal friction angle of the intact block. Hence, in order to determine the friction angle along the shear surface on the presence of this type of rock bridges, it is possible to use the following equation:

$$\phi_{RB} = \phi_i \quad (1)$$

where φ_{RB} is the friction angle along the shear surface, and φ_i is the internal friction angle of the intact mass. The variance in the cohesion of the rock bridges based on the increase in the normalized area is shown in Figure 6b. As it is observed, if the equation (A/A') is considered equal to 1, the cohesion produced (14/9 kg/cm^2) is approximately equal to the cohesion of the intact mass (13/765 kg/cm^2). Hence, in order to determine the cohesion along the shear surface on the presence of this type of rock bridges, it is possible to use the following equation:

$$c_{RB} = (\mathrm{A/A'})\ c_i \quad (2)$$

where c_{RB} is the cohesion along the shear surface, A is the area of the rock bridge, A' is the total area of the shear surface, and c_i is the cohesion of the intact mass.

3.3. Validation of previous criteria in predicting shear strength of non-persistent joint

The parameters of shear strengths for rock bridges and discontinuities are used in Jennings [39] criterion for predicting the shear strength of a non-persistent jointed rock mass (Eq. 3). In this criterion, the linear connectivity rate of joints is used to estimate the shear strength of a jointed rock mass. The Jennings criterion is widely used for predicting the shear strength of rock masses but in some cases the assumption of decreasing the shear strength linearly with the increase in connectivity rate of discontinuities may not truly reflect the real characteristics of the rock [18, 19].

$$\tau = c + \sigma_c\, tan\varphi = k\sigma c_d + (1 + k)c_r + \sigma_n[\mathrm{k}\tan\varphi_d + (1 - k)\tan\varphi_r] \quad (3)$$

where τ is the peak shear strength; σ_n is the normal stress; k is the connectivity rate; c, c_d, and c_r denote the cohesion of a rock mass, discontinuities, and rock bridges, respectively; and φ, φ_d, and φ_r denote the friction angle of a rock mass, discontinuities, and rock bridges, respectively.

Some researchers [28] proposed some modification on the Jennings criterion. They suggested the joint roughness condition (JRC) and cohesion decrease in rock bridges between the discontinuities. Tang *et al.* [19] considered the weakening of strength parameters (cohesion and friction angle) of rock bridges in the jointed rock masses. The modified Jennings criterion could not overcome all the shortcomings of the non-linearity of the failure process in the jointed rocks. Therefore, the researchers tried to study the progressive failure of jointed rock masses under various loading environments (static and dynamic loadings) based on different experimental tests and numerical simulation procedures [41-45]. Some good laboratory tests carried out by Guo *et al.* [40] and a comprehensive strength model proposed to study the tensile and shear strengths of jointed rock masses. They concluded that decrease in cohesion and rise in friction angle decrease the tensile strength and increase the shear strength of a jointed rock mass. The plastic strain changes are nonlinear and the damages of the rock structure enhances due to tensile strength loss of the rock.

The nonlinear treatment of shear failure in rock masses with non-persistent joints may provide good understandings of instability analyses and improving the design issues related to rock slopes and underground rock structures.

$$\tau_f = \sigma_c\, tan\varphi(\gamma_p) + c(\gamma_p), \sigma_t = \sigma_t(\varepsilon_t^p) \quad (4)$$

where (γ_p) and $c(\gamma_p)$ denote the residual cohesion and friction angle of the jointed rock during the plastic shear strain at shear failure; the tensile strength term $\sigma_t(\varepsilon_t^p)$ is due to the plastic tensile strain term of the nonlinear failure criterion in Eq. (4). The progressive failure of rock bridges may exert nonlinear mechanical characteristics to the non-persistent jointed rock structures. Therefore, in this work, a suitable non-linear criterion is proposed to analyze the rock testing data published in the literature.

The results of shear strengths obtained from the experimental tests are estimated based on Jennings's criterion and Guo and Qi's criterion are presented in Figure 7. The experimental values of shear strengths are a little bit lower than those estimated from Jennings's criterion and Guo and Qi's criterion. Comparing the shear strengths of Guo and Qi's and Jennings's criteria [39, 40] with the corresponding experimentally measurement results show that the nonlinear Guo and Qi's criterion provides more reliable shear strengths for the non-persistent jointed rocks. However, the following conclusions may give a clear practical application of Guo and Qi's criterion for predicting the non-linear shear strength of non-persistent jointed rocks.

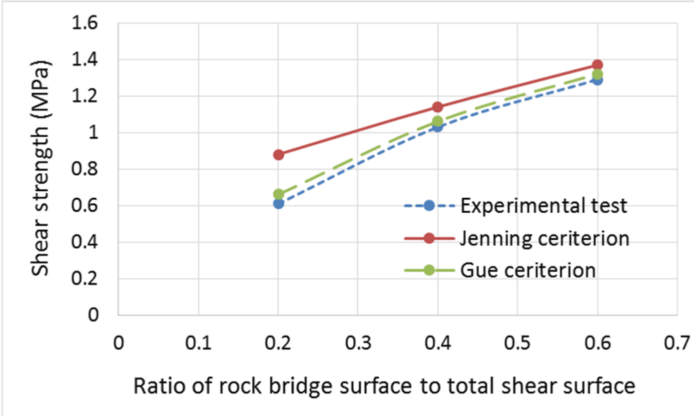


Figure 7. Shear strength determined by experimental test, jenning criterion, and Guo and Qi's criterion.

4. Conclusions

- In the fixed area of the rock bridge, the shear resistance along the shear surface remains approximately constant by increasing in the number of continuous rock bridges.
- In the fixed area of the rock bridge, the cohesion along the shear surface shows a small decrease, by increaseing in number of persistent rock bridges.
- The areas of weak planes along the shear path were increased by increasing the number of rock bridges. Hence, with the increase in number of weak points, the concentration of stress around the rock bridges is increased, which results in a reduction of cohesion.
- Since the increase in number of rock bridges in the fixed area of the rock bridge results in a small reduction in cohesion, hence it is possible to ignore this effect.
- The increasing of area in various types of rock bridges has no measurable effect on the friction angle along the shear surface.
- With the increase in area of various types of rock bridges, the cohesion along the shear surface approximately shows a linear increase.
- The non-linearity of the cohesion and friction angle as the two main strength parameters in the progressive failure process of non-persistent jointed rock mass has been involved in the Guo and Qi's criterion.
- The Jennings criterion estimates some lower values of rock shear strength compared to the experimentally measured values in the laboratory.
- It should be noted that in the Jennings criterion, the strength parameters are linearly related to each other using a rock mass connectivity rate parameter showing the effects of non-persistency in the rock joints.
- The Guo and Qi's criterion gives more relatable shear strength values compared to those estimated using Jenning's criterion. It means that the non-linear behavior of rock bridges in the non-persistent jointed rocks can be modelled by Guo and Qi's criterion.

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بررسی ویژگی‌های برشی ناپیوستگی‌های عرضی باز ناممتد هم سطح

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چکیده:

در این مقاله، تأثیر تغییرات تعداد و منطقه پل‌های سنگی بر ناپیوستگی‌های ناممتد بررسی می‌شود. در این راستا بلوک های حاوی پل های سنگی و درزهایی به ابعاد 15 cm×15cm×15cm از گچ تهیه شده است. پل های سنگی موجود که 0/2، 0/4 و 0/6 از سطح برشی را اشغال کرده‌اند، امتداد عرضی را در امتداد سطح برشی نشان می‌دهند. در تعداد و گسترش پل‌های سنگی در منطقه ثابت تغییراتی وجود دارد .برای هر یک از نمونه‌ها، آزمایش‌هایی بر روی سه بلوک از یک ماده با قرار دادن آن‌ها تحت تنش‌های نرمال مستقیم مختلف انجام می‌شود. تنش‌های نرمال 3/33، 5/55، 7/77 Kg/cm^2 بود. همچنین مقاومت برشی به‌دست‌آمده با آزمایش‌های آزمایشگاهی با خروجی‌های معیار جنینگ و معیار گوو مقایسه شد تا دقت این معیارها برای پیش‌بینی مقاومت برشی درزه‌های ناممتد مشخص شود. نتایج نشان می‌دهد که ترک کششی در پل سنگی تحت تنش نرمال 3/33 Kg/cm^2 شروع شده است. ترک‌های برشی کششی حالت مختلط در پل سنگی تحت تنش معمولی 5/55 Kg/cm^2 منتشر شدند، در حالی که یک ترک برشی خالص در پل سنگی تحت تنش معمولی 7/77 Kg/cm^2 ایجاد شد. با افزایش تنش نرمال، تعداد ریزشکستگی‌ها افزایش یافت. واریانس تعداد پل‌های سنگی در ناحیه ثابت پل سنگی بر زاویه اصطکاک در امتداد سطح برشی تأثیر نمی‌گذارد. علاوه بر این، چسبندگی در امتداد سطح برشی با افزایش تعداد پل‌های سنگی کاهش کمی نشان می‌دهد. همچنین با افزایش ناحیه پل‌های سنگی، زاویه اصطکاک در امتداد سطح برشی ثابت می‌ماند و در عین حال، چسبندگی تقریباً خطی افزایش می‌یابد .معیارگو مقاومت برشی درزه ناممتد را دقیقاً نزدیک به مقاومت برشی نمونه‌های فیزیکی پیش‌بینی می‌کند.

کلمات کلیدی: پل سنگی، شکست برشی، خواص برشی، درزه ناممتد.