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Impact of Infill Materials of Discontinuities with Different Orientations on Triaxial Compressive Strength of Jointed Rock

Hadi Mokhtarian[1], Majid Noorian-Bidgoli[1], Hassan Moomivand[2]

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ABSTRACT

Geological discontinuities can be infilled or unfilled, with the infilled type being the most common. Various materials with different compositions and strengths can fill these discontinuities. Previous studies have used plaster, sand, and clay mixtures to model infill materials. This study prepared three infill materials with uniaxial compressive strengths (UCS) of 0.616, 2.203, and 3.920 MPa by mixing plaster, sand, and clay with water in different weight ratios. A total of 180 triaxial compressive strength tests were conducted to evaluate the impact of these materials on the axial strength of specimens with discontinuities oriented at angles of 30°, 45°, 60°, and 90°. These tests were performed under confining pressures (CP) ranging from 0 to 20 MPa. Observations revealed a failure in intact rock fragments for discontinuities oriented at 0 and 90°. Axial strength significantly decreased, showing reductions of about 22%, 33%, and 67% for UCS values of 3.920, 2.203, and 0.616 MPa, respectively, when comparing 90° to 30° orientations. Indeed, the failure occurred within the lower-strength infill material, while for the more robust infill material, it happened on the interface of the discontinuity and the infill material. With increasing the CP, no significant change was seen in the decreasing trend of the axial strength with increasing the orientation angle in the range of 30° to 90°. The type of infill materials did not impose any significant effect on the axial strength at lower CPs. At higher CPs, however, the axial strength was seen to increase with increasing either the uniaxial strength, internal friction angle, and sand content of the infill material. In all tests, the obtained axial strength was lower than that predicted by the Jaeger theory.

KEYWORDS

Strength, Jointed rock, Discontinuity, Triaxial stresses, Infill materials

I. INTRODUCTION

The overall strength of rock masses is profoundly influenced by discontinuities, with their mechanical properties being regarded as the primary determinant in rock strength reduction. While the shear strength of these discontinuities has been predominantly studied through direct shear tests in previous research, the inherent complexity of characterizing the shear resistance and other properties has become apparent (Hobbs, 1968; Brown & Trollope, 1970; Einstein & Hirschfeld, 1973; Jaeger, 1960; Vutukuri & Moomivand, 1996; Saucier, 1967; Stimpson, 1970; Karakul et al., 2010; Verma & Singh, 2010).

Valuable insights have been gained from these tests, conducted under two boundary conditions: constant normal load/stress (CNL) and constant normal stiffness (CNS). In CNL conditions, where normal stress remains constant, joint surfaces dilate freely during shearing. Conversely, in CNS conditions, joint dilation is constrained, resulting in higher peak shear strength, friction angle, and cohesive strength values. Consequently, CNS tests offer a more comprehensive representation of the influence of rock joint roughness than CNL tests. However, replicating the complexity of CNL and CNS conditions poses challenges when testing joint specimens under triaxial compressive stresses.

Recent research has shed light on the influence of natural infill materials on discontinuity strength parameters. Jahanian and Sadaghiani (2015) studied the shear strength of rough joints made from sandy clay-infilled saw-tooth structures under controlled normal loading (CNL) conditions. They highlighted that the thickness of the infill had limited influence compared to the surface roughness and the inclination of the asperities, even at higher levels of normal stress. Similarly, the effect of infill thickness on joint compressive strength (JCS) and overall shear strength was explored by Karakus et al. (2016), who also conducted their experiments under CNL conditions. They noted minimal variations in JCS up to a threshold infill thickness of 2 mm. Their findings led to the proposal of a novel shear strength model for rock joints,

[1] Department of Mining Engineering, Faculty of Engineering, University of Kashan, Kashan, Iran, [2]Department of Mining Engineering, Faculty of Engineering, Urmia University, Urmia, Iran

M. Noorian-Bidgoli: noriyan@kashanu.ac.ir

integrating infill thicknesses ranging from 1 to 6 mm and emphasizing the interaction between joint surface and infill material.

Recent research has further delved into the impact of discontinuity orientation on unfilled jointed rock strength under triaxial stresses, focusing on evaluating rock failure criteria parameters based on unfilled jointed specimens. (ASTM, 1997; Barton, 1976; Muralha et al., 2014). Cylindrical plastic specimens with undulating and planar discontinuity surfaces were investigated by Sinha and Singh (2000), who employed pulverized gouge as infill material. Their findings underscored the significant influence of infill material on specimen strength and mechanical behavior, particularly under specific conditions.

Mokhtarian et al. (2020) investigated the influence of infilled discontinuities on rock failure mechanisms under triaxial stresses. To this end, they created three infilled discontinuities using different infill materials with varying compositions and uniaxial compressive strengths (UCSs). Triaxial tests on cylindrical specimens revealed that failure occurred predominantly along infilled discontinuities at specific orientation angles, with stronger infill materials resulting in shear failure at the interface between the infill material and the rock. The study highlighted the impact of infill material composition and orientation angle on jointed rock failure criteria parameters, establishing new relationships between these factors. These tests were performed under CNS conditions.

Xu et al. (2024) investigated the profound impact of stiff discontinuities on deep hard rock engineering disasters. The authors analyzed their influence on deformation and failure mechanisms during excavation through true triaxial tests on marble samples containing natural stiff discontinuities. Parameters such as discontinuity inclination angles, thicknesses, and stress states were examined across various true triaxial stress conditions. The experimental results demonstrated that the samples' post-peak deformation and failure characteristics are significantly affected by the inclination angle, thickness, and stress state of the stiff discontinuity. Specifically, conditions featuring high minimum principal stress, low intermediate principal stress, thick stiff discontinuity, and an inclination angle close to the failure angle of intact samples resulted in microcracks being primarily controlled by the stiff discontinuity, rendering the sample more prone to sudden and violent tensile failure along the discontinuity. These experiments likely involved CNS conditions due to the consideration of stiffness constraints.

Wu et al. (2024) focused on the shear strength deterioration of bedding planes between different rock types induced by cyclic loading. The aim was to evaluate the stability of interbedded bedding rock slopes under earthquake conditions. They investigated the shear strength weakening of discontinuities with different joint wall materials (DDJM) under cyclic loading, utilizing samples from the Shaba slope in Yunnan Province, China. Through experimental investigations, the authors examined the influence of various factors such as normal stress, joint surface morphology, shear displacement amplitude, and shear rate on the shear strength changes of DDJMs over cyclic loading cycles. The results highlighted the importance of understanding these factors in assessing the stability of interbedded rock slopes under dynamic loading conditions.

Despite these advancements, gaps persist in understanding how infill material properties influence discontinuities with varying orientations on failure mechanisms and jointed rock failure criterion parameters under triaxial compressive stresses. This study seeks to bridge this gap by identifying the effect of infill material properties on jointed rock failure criterion parameters under triaxial compressive stresses. These tests were conducted under CNL conditions.

In the present study, physical modeling was utilized to prepare infill materials with varying UCSs, offering a valuable tool for investigating the mechanical behavior of heterogeneous materials like rock. Due to its uniform texture and suitability for this purpose, Naghdeh limestone was employed to prepare the jointed specimens. Additionally, the failure criteria of Hoek and Brown (2002) and Ramamurthy (2001) were applied to analyze the test results, given their effectiveness in representing the rock strength with discontinuities, particularly under triaxial compressive stresses.

II. Preparing and Testing the Specimens

Compositions of plaster, sand, and clay were used to prepare model infill materials. This was done because of the similar behavior of this mixture to natural infill materials in the opening of discontinuities. Three model compositions were prepared by mixing the plaster, sand, and clay into water at different ratios. The ratio by weight of cement (Cc), sand (Sc), plaster (Pc), and water (Wc) are shown in Table 1. Table 2 indicates the particle size distribution of the sand utilized in this study. Subsequently, cylindrical standard specimens (ASTM, 1997) were prepared from the mortar obtained from infill materials. Drained UCS measurements were then performed on the cylindrical specimens based on the relevant standard procedure (ASTM, 1997). Table 3 shows the results of the UCS tests. Shear strength was then measured on jointed limestone specimens where the discontinuities were filled with either of the three types of infill materials with a thickness of 6 mm; this was done by a direct shear test based on the relevant standard procedure (Barton, 1976; Muralha et al., 2014) to determine the internal friction angle (ϕ_j) and cohesion (C_j), with the results presented in Table 3.

To investigate the effect of infill materials on the failure criterion of discontinuities oriented at different angles (measured from the horizontal axis) under triaxial stresses, cylindrical limestone specimens with discontinuities oriented at 0, 30, 45, 60, and 90° were prepared, as per created the relevant standard (Fig. 1), and then the opening of the discontinuities were infilled by either of the three model infill materials (Fig. 2). The discontinuities with different orientation angles were made with the help of a diamond saw in the rock mechanics laboratory. The model infill materials used to fill in the opening of the discontinuities came with different strength levels of 0.616, 2.203, and 3.920 MPa with a thickness of 6 mm (Fig. 3). Previous studies indicated that the shape, size, and roughness of wall surface do not affect the cohesion and friction angle since the discontinuity walls were not in contact with each other upon filling.

(Barton, 1976).

The specimens' strength was measured upon draining through triaxial compression testing under a confining pressure of 0 to 20 MPa, based on the relevant standard procedure (Barton, 1976; Kovari et al., 1983; ASTM, 1997; Muralha et al., 2014). The results of the triaxial tests, along with the determination of the internal friction angle and cohesive strength by fitting the best-fit line to the data points, are presented in the appendix.

Table 2. PARTICLE SIZE DISTRIBUTION OF THE SAND EMPLOYED FOR PREPARING THE MODEL INFILL MATERIALS IN THIS STUDY.

No.	Particle size	wt.%
1	Passing through a 2.36 mm sieve	100
2	Passing through a 1.18 mm sieve	90
3	Passing through a 0.6 mm sieve	46.2
4	Passing through a 0.3 mm sieve	17.5
5	Passing through a 0.15 mm sieve	4.3

Table 3. UCS in Model Materials, as well as Friction Angle (ϕ_j) and Cohesion (C_j) in Three Types of Model Infill Materials in the Aperture of the Discontinuity

Infill material	Average UCS σciav (MPa)	Standard deviation (MPa)	Friction angle (ϕ_j) Degree	Cohesive strength (C) (MPa)
F1	3.92	0.13	32.10	1.83
F2	0.62	0.08	34.34	1.77
F3	2.20	0.17	36.68	0.927

As shown in Fig. 4, failure occurs in intact rock fragments in specimens with discontinuities orientation angle 0°. However, the infill material with lower strength is more pulverized. Figs. 5-7 illustrate that failure occurs in the discontinuity plane for the orientation angles of 30, 45, and 60°. As demonstrated in Figs. 6 and 7, for infill materials of higher uniaxial strength, failure occurs at the contact surface of the discontinuity wall with the infill material. However, failure occurs in the infill material for the infill material with lower uniaxial strength (Fig. 5). As displayed in Fig. 8, failure occurs in the intact rock fragments, and the infill material with lower strength is more pulverized in the specimens with discontinuities, oriented at 90°.

Fig. 1. A group of specimens prepared based on the standard defined by the International Society of Rock Mechanics (ISRM) (1979)

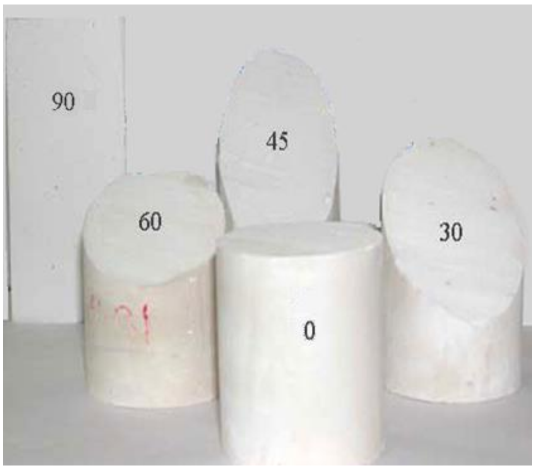

Fig. 2. Examples of the discontinuities made at different orientation angles

Table 1. Composition of the Model Infill Materials Used to Fill the Opening of the Discontinuities in his Research

Infill material	$\frac{C_c}{C_c+S_c+P_c+W_c}$	$\frac{S_c}{C_c+S_c+P_c+W_c}$	$\frac{P_c}{C_c+S_c+P_c+W_c}$	$\frac{W_c}{C_c+S_c+P_c+W_c}$
F1	-	0.40	0.30	0.30
F2	0.25	0	0.38	0.38
F3	0.17	0.33	0.17	0.33


Fig. 3. Specimens with discontinuities at different orientations upon filling with the model infill materials.


Fig. 4. Failure in the intact body of the specimen with a discontinuity oriented at 0°.


Fig. 5. Failure along the discontinuity plane for the specimen containing an infilled discontinuity oriented at 30°.


Fig. 6. Failure along the discontinuity-infill material interface for stronger infill materials. The discontinuity is oriented at 45°.

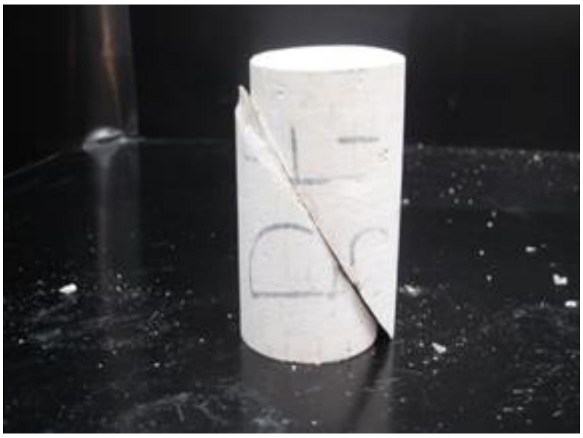
Fig. 7. Failure along the discontinuity-infill material interface for stronger infill materials. The discontinuity is oriented at 60°.


Fig. 8. Failure in the intact body of the specimen with an infilled discontinuity oriented at 90°.

III. Effects of Infill Material and Discontinuity Orientation on the Rock Strength under Triaxial Stresses

Association of the axial strength (σ_1) with the orientation angle of the discontinuity (α) was studied under different CPs based on the results of triaxial compressive strength tests on the specimens where the discontinuity was filled by different infill materials, with the results shown in Figs 9-11. These results indicate that the axial strength (σ_1) exhibits some negligible drop as the orientation angle (α) increases from 0 to 30° under constant CP. However, a further increase of the orientation angle from 30 to 45 and then 60° decreased the axial strength (σ_1) significantly. Minimum axial strength (σ_1) was obtained at an orientation angle of 60°. Conversely, as the orientation angle increased from 60° to 90°, the axial strength (σ_1) exhibited an increasing trend.

Results further depict that an increase in the CP decreases the effect of the orientation angle (α) on the axial strength (σ_1) as the specimens with discontinuities became stronger at higher CPs, with their strengths approaching that of intact rock. At orientation angles of 0 and 90°, the axial strength (σ_1) of the jointed rock was below that of intact rock, implying that the presence of discontinuities negatively affects the axial strength (σ_1) regardless of the discontinuity orientation, even when the joints are perpendicular to the principle stress directions. Fig. 12 compares the results for the specimens with discontinuities at different orientation angles filled with different infill materials under different CPs. Based on the results of the triaxial tests, for all three model infill materials, uniaxial strength, axial strength, cohesion, and friction angle remained almost unchanged under low CPs. However, an increase in the CP led to higher levels of axial strength (σ_1) in the specimens where the infill material exhibited greater uniaxial strength, friction angle, and sand content. This highlighted that the type of infill material and its mechanical properties (e.g., uniaxial strength and friction angle) are more effective at higher stress levels. Additionally, a significant reduction in axial strength was observed with changes in orientation angles. Specifically, when comparing discontinuities oriented at 90° to those at 30°, the reduction in axial strength was approximately 22% for UCS = 3.920 MPa, 33% for UCS = 2.203 MPa, and 67% for UCS = 0.616 MPa. These findings emphasize that the influence of orientation and infill material properties becomes more pronounced under higher stress levels.

IV. Analyzing the Results Using the Jaeger Failure Criterion

Jaeger (1960) proposed the following model to express the relationship between axial strength (σ_1) and discontinuity orientation angle (α) under constant CP (σ_3).

$$\sigma_1 - \sigma_3 = \frac{2(c_j + \sigma_3 \tan\phi_j)}{(1 - \tan\phi_j \cot\alpha)\sin 2\alpha} \qquad (1)$$

Figs. 13-15 compare the outputs of the Jeager theory with the experimental data obtained from the triaxial compressive strength tests in this study. Based on the results, the Jeager theory tends to overestimate the axial strength in all cases. This is because a significant portion of the discontinuity is filled, and the Jaeger theory does not account for their strength under triaxial stresses. This finding is remarkable as the Jaeger theory is currently serving as the main tool for determining the axial strength of discontinuities in such famous software packages as FLAC (Board, 1989). An increase in the CP decreases the extent of the parabolic region along the curve, representing the relationship between the axial strength (σ_1) and the orientation angle in Jaeger's theory. In addition, the parabolic region disappears at high CPs. This problem is intensified as the friction angle increases.

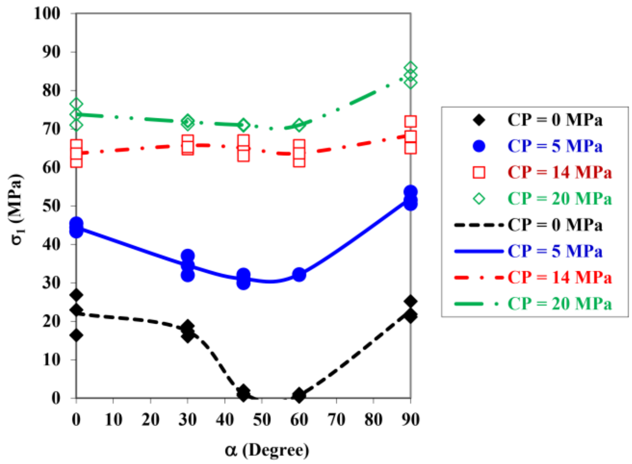

Fig. 9. Relationship between axial strength and orientation angle for discontinuities filled by an infill material of 0.616 MPa in uniaxial strength under different CPs.

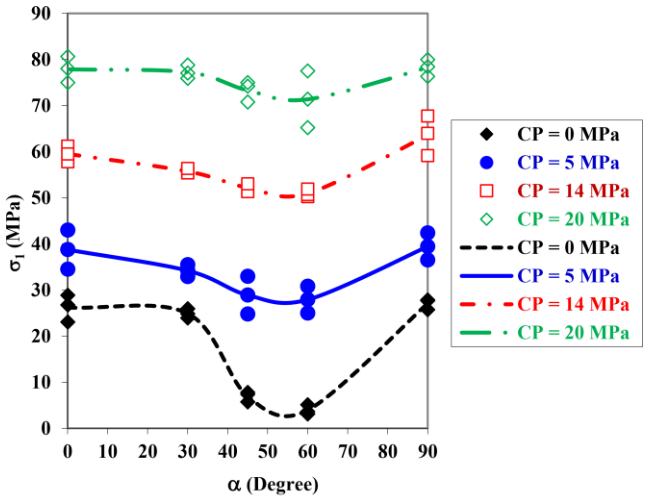

Fig. 10. Relationship between axial strength and orientation angle for discontinuities filled by an infill material of 2.203 MPa in uniaxial strength under different CPs.

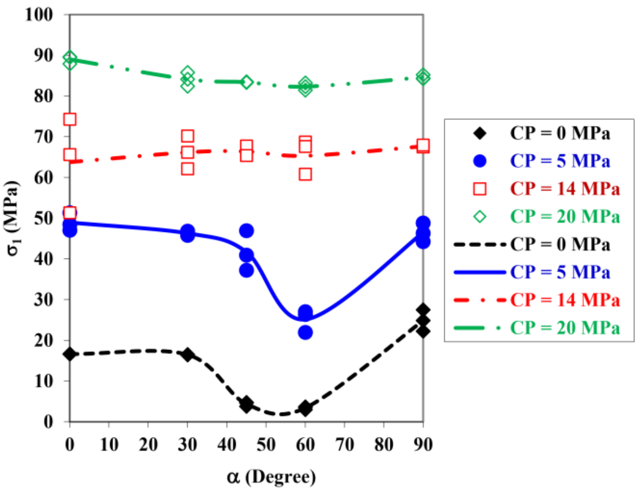

Fig. 11. Relationship between axial strength and orientation angle for discontinuities filled by an infill material of 3.920 MPa in uniaxial strength under different CPs.

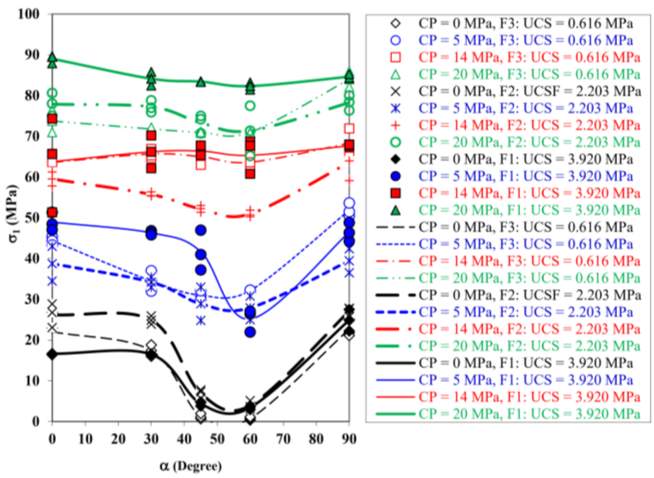

Fig. 12. Comparing the relationship between axial strength and orientation angle for discontinuities filled with different infill materials having different UCS under different CPs.

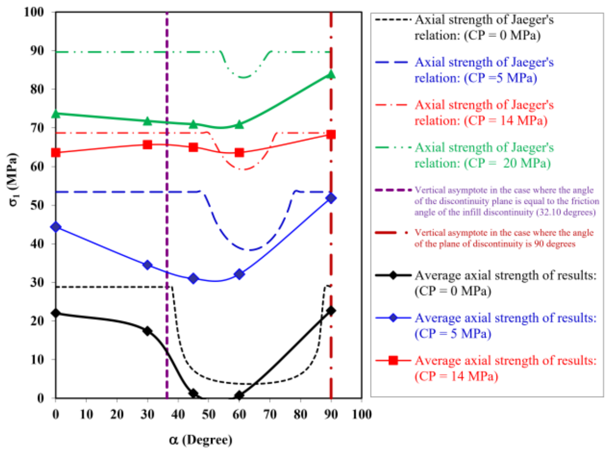

Fig. 13. Comparing Jeager theory with measured data focuses on the relationship between the average axial strength and orientation angle for the discontinuity filled by the model infill material with a UCS of 0.616 MPa under different CPs.

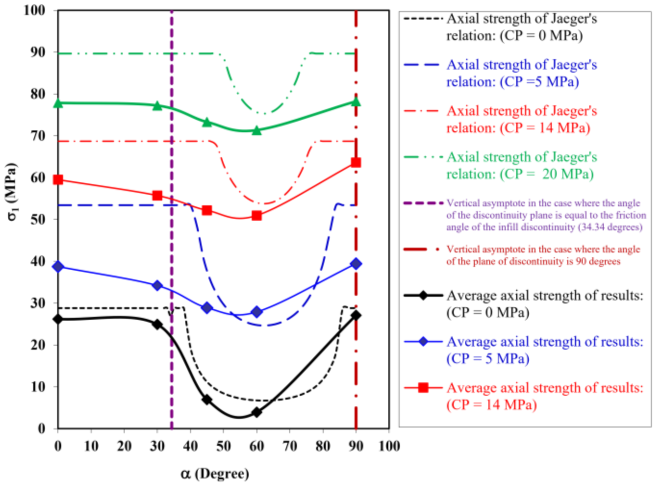

Fig. 14. Comparing Jeager theory with measured data focuses on the relationship between the average axial strength and orientation angle for the discontinuity filled by the model infill material with a UCS of 2.203 MPa under different CPs.

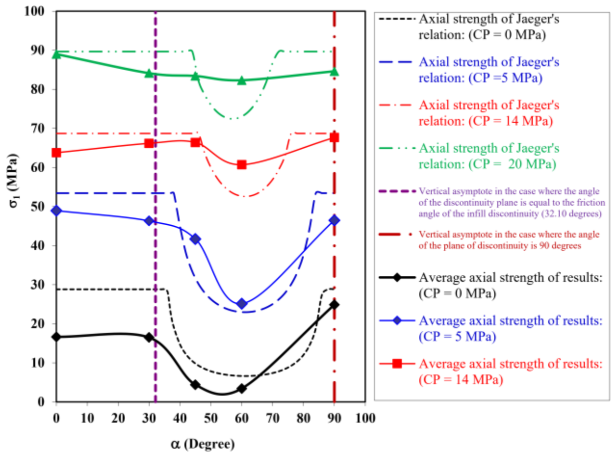

Fig. 15. Comparison between estimated axial strength (σ_1) by Jaeger theory and σ_1 of the results as a function of orientation angle (α) under different confining pressures (CP) for discontinuities with infill materials type F1

V. CONCLUSION

1. Failure occurred in intact rock fragments in the specimens with discontinuities oriented at 0° or 90°. However, the infill material with lower strength was more pulverized.
2. Failure occurred on the discontinuity plane for discontinuities oriented at 30, 45, and 60°. In addition, failure occurred along the discontinuity wall-infill material interface when the infill material exhibited more strength. For weaker infill materials, however, failure occurred within the infill material.
3. The axial strength (σ_1) of jointed rocks with discontinuities oriented at either 0° or 90° was lower than that of intact rock, indicating the adverse effect of discontinuities on the rock mass strength even when the joint orientation is perpendicular to the principal stresses.

4. An increase in CP negligibly decreases the axial strength, with intensifying the effect as the orientation angle increases from 30° to 90°.

5. An increase in the CP increases the axial strength (σ_1) in the specimens where the infill material exhibits higher UCS, friction angle, and sand content. This suggests that the composition of the infill material and its mechanical properties (*e.g.*, UCS and friction angle) are more effective at higher stress levels.

6. The observed axial strength was generally less than estimations by the Jaeger theory in all studied cases.

7. These findings emphasize the crucial importance of the properties of infill materials, joint orientation, and confining pressure in designing engineering structures within jointed rock masses. For instance, weaker infill materials can significantly weaken the stability of the rock mass, necessitating additional reinforcement measures. Additionally, the orientation of discontinuities must be carefully considered in excavation and tunneling projects, as specific angles, such as 30° and 45°, exhibit the lowest axial strength, increasing the risk of failure.

Future research could examine the effects of various infill materials, including those with different chemical compositions or additives, on joints' behavior and failure mechanisms. Additionally, testing under diverse environmental conditions—such as changes in moisture levels and temperature fluctuations—would provide a deeper understanding of the durability and strength of jointed rock masses in real-world settings. It is also essential to consider the impact of joint surface roughness, as it significantly influences the failure mechanisms and shear strength of rock masses, especially under varying stress conditions.

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