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Reconstruction of Shear Surface Based on Joint Roughness Coefficient and Its Relation to Rock Shear Strength

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Abstract

Rock strength is a fundamental parameter in rock mechanics, serving as the basis for predicting rock behavior under various loading conditions. Among the various approaches to characterizing rock strength, shear testing of discontinuities plays a crucial role. The Joint Roughness Coefficient (JRC) provides an empirical link between joint surface roughness and shear strength parameters. In this study, joint surface profiles were reconstructed statistically based on JRC parameters and subsequently reproduced using three-dimensional (3D) printing technology. The printed molds were employed to cast laboratory specimens with pre-formed shear surfaces, which were then tested under direct shear conditions. The shear strength parameters obtained from the tests were analyzed in relation to their corresponding JRC values. The results demonstrate that the reconstructed and 3D-printed surfaces were successfully fabricated and accurately replicated joint roughness geometries. Direct shear tests confirmed the expected trend, with shear strength increasing alongside JRC. These findings indicate that shear surfaces can be prefabricated and manipulated with controlled roughness, providing a reliable and reproducible platform for investigating the mechanical behavior of rock joints.

1. Introduction

Rock mass strength is a fundamental parameter in rock mechanics, forming the basis for predicting rock behavior under various loading and environmental conditions. A critical component of rock mass strength is the shear strength of discontinuities (joints) within the rock mass. Barton (1974) and Barton et al. (2023) introduced the Joint Roughness Coefficient (JRC) as a quantitative descriptor of shear surface roughness, identifying it as one of the key parameters influencing joint shear strength. The JRC concept provides ten standard surface roughness profiles that serve as reference patterns for field or laboratory determination, allowing the comparison of actual shear surfaces with the reference set (Figure 1).

Concurrently, additive manufacturing, also known as 3D printing, has revolutionized multiple industries by enabling the construction of three-dimensional objects layer by layer through techniques such as fused deposition modeling (FDM), stereolithography (SLA), and selective laser sintering (SLS). Compared to conventional manufacturing methods, 3D printing offers greater flexibility, accuracy, and the ability to reproduce complex geometries with fine detail (Zhou and Zhu, 2017). These capabilities have been successfully applied in diverse fields, ranging from biomedical applications such as prosthetics and anatomical models to lightweight components in the automotive and aerospace sectors (Frazier, 2014).

Each method has its unique advantages: FDM is cost-effective and user-friendly, SLA achieves high precision and fine detail, and SLS enables the production of strong and functional parts. More recently, 3D printing has been introduced into rock mechanics research, including the direct printing of 3D-scanned rock specimens (Huang et al., 2023).

Building on these developments, this study explores the potential of integrating statistical and spatial representations of rock joint roughness with 3D printing technology. Specifically, rock shear surfaces are reconstructed from statistical descriptors of roughness and physically reproduced using 3D printing. This approach provides a novel platform for systematically testing the relationship between JRC and shear strength using 3D-printed specimens. Such investigations are expected to validate the feasibility of 3D surface reconstruction and offer a more robust understanding of how joint roughness, represented by JRC, influences rock shear strength.

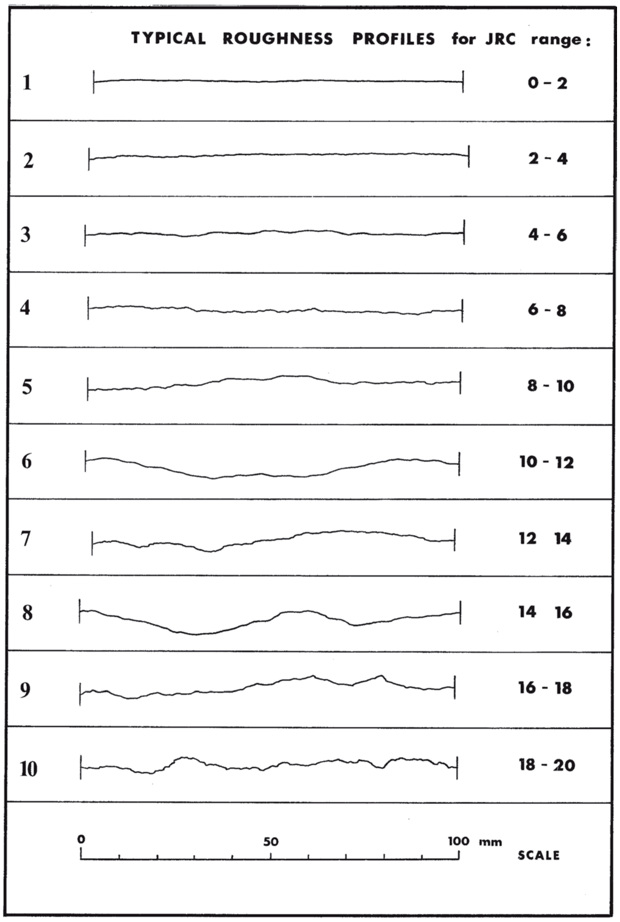


Figure 1. Typical surface roughness profiles representing the Joint Roughness Coefficient (JRC) ranges, after Barton (1974).

2. Data and methods

The surface reconstruction methodology employed in this study builds upon the approach proposed by Liu et al. (2022). Each standard roughness profile from Barton's reference chart (Figure 1) was divided into 5 mm segments. For each segment, two key parameters were quantified: the angle of ascent or descent (θ_i) and the sequence of consecutive ascending or descending segments (S_i), as illustrated in Figure 2. These parameters were then statistically analyzed to characterize the roughness features, which served as the basis for reconstructing the surface geometry.

The reconstructed datasets were found to follow an approximately normal distribution. Therefore, random numbers could be generated based on the mean and standard deviation of the measured parameters (Table 1). To reconstruct the profiles, the mean and standard deviation of the sequence length (S_i) were used to generate a set of random values with a total length of 120 segments (equivalent to 60 mm). These values determined whether each segment was ascending or descending (Figure 3a). Subsequently, the mean and standard deviation of the climbing angle (θ_i) were applied to assign slope angles to the respective segments, completing the reconstruction of the surface profile (Figure 3b).

To create physical molds, the reconstructed 2D profiles were imported into AutoCAD (Figure 4a), extruded perpendicular to the profile plane with a height of 10 mm (Figure 4b), and shaped into cylindrical specimens to replicate direct shear sample geometry (60 mm diameter, 70 mm height) (Figure 4c). The final 3D models were printed using an AnyCubic Photon Mono 2 printer (Figure 4d).

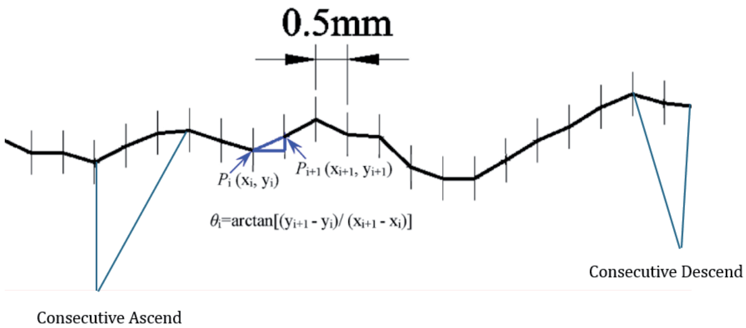


Figure 2. Illustration of climbing angle (θ_i) and consecutive ascent/descent segments (S_i).

Table 1. Statistical parameters of climbing angle (θ_i) and consecutive ascent/descent (S_i) as reported by Liu et al. (2022).

Note		**Climbing Angle (θi)**		**Consecutive Ascend or Descend (Si)**	
JRC	Profile	Mean (μ)	Standard Deviation (σ)	Mean (μ)	Standard Deviation (σ)
0 to 2	1	0.19	9.36	-0.3	1.44
2 to 4	2	0.67	9.65	-0.07	1.13
4 to 6	3	0.43	10.15	-0.05	1.58
6 to 8	4	-0.18	13.93	-0.01	1.3
8 to 10	5	1.35	13.35	-0.02	1.96
10 to 12	6	-0.42	12.66	-0.32	3.63
12 to 14	7	0.62	15.31	0.05	1.84
14 to 16	8	0.06	16.65	0.26	2.63
16 to 18	9	1.26	17.94	0.19	2.38
18 to 20	10	-0.2	21.89	0.06	1.78

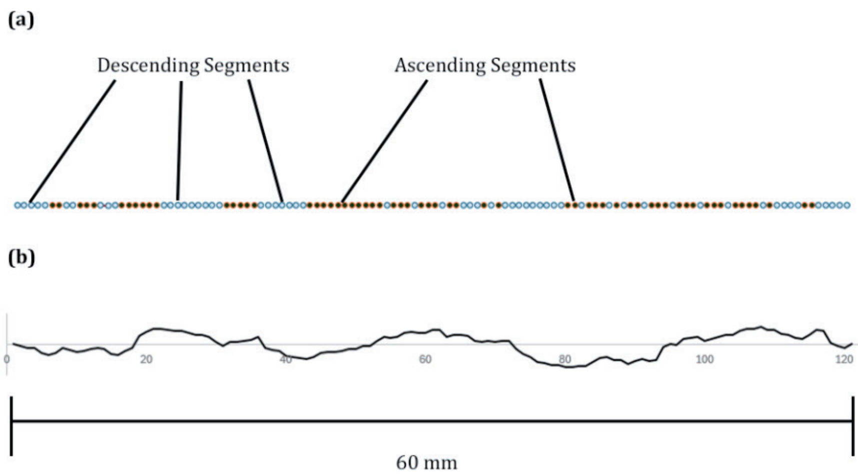


Figure 3. Example of reconstructed profiles generated from random number series: (a) consecutive ascent or descent sequence, and (b) climbing angle assignment.

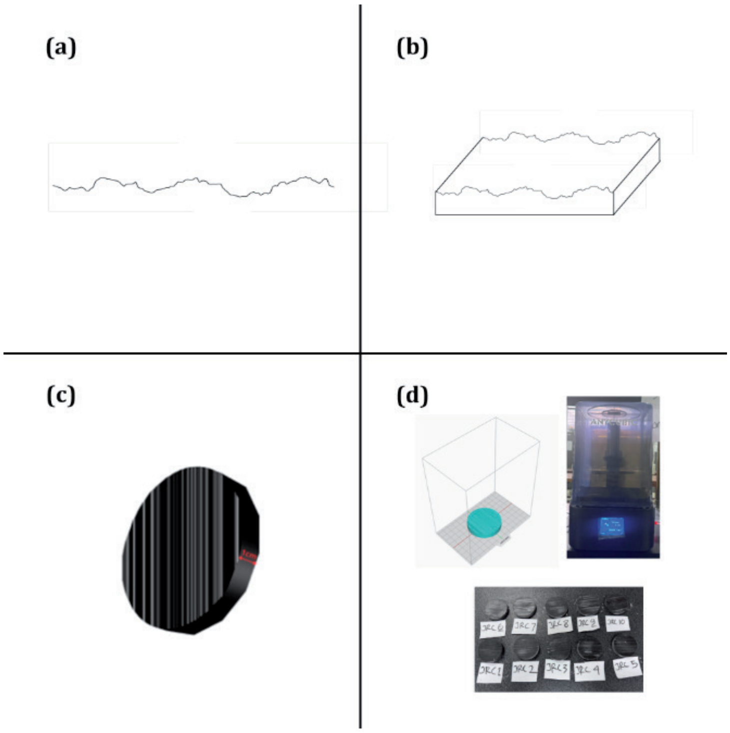


Figure 4. Procedure for generating shear surface molds using 3D printing: (a) conversion of the 2D profile into AutoCAD, (b) extrusion of the profile, (c) shaping into cylindrical specimen geometry, and (d) final 3D-printed mold.

The laboratory samples were prepared using a gypsum–water mixture at a 4:3 weight ratio. A PVC pipe (60 mm diameter, 70 mm height) was cut and filled to half its height (35 mm) with the mixture (Figure 5a). The 3D-printed mold was then embedded on top of the mixture for 15 minutes to imprint the shear surface at mid-height (Figure 5b). After curing, the mold was removed (Figure 5c), and the pipe was filled to the top with the same mixture (Figure 5d).

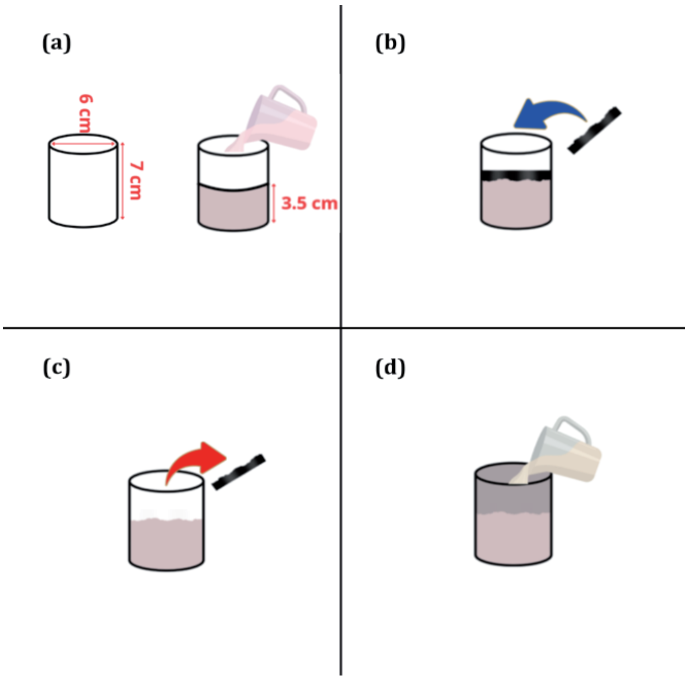


Figure 5. Process of fabricating laboratory specimens with pre-formed shear surfaces: (a) filling the pipe mold to half height with gypsum–water mixture, (b) embedding the 3D-printed mold to imprint the shear surface, (c) removal of the mold after curing, and (d) completion of specimen filling.

The shear direction of each specimen was marked to be perpendicular to the reconstructed profile, ensuring that the roughness geometry exerted its full influence during testing. Direct shear tests were then conducted to evaluate the relationship between surface roughness and shear strength. In addition, companion specimens of the same material composition were prepared to determine the basic physical properties, as summarized in Table 2.

Table 2. Physical properties of the prepared laboratory specimens.

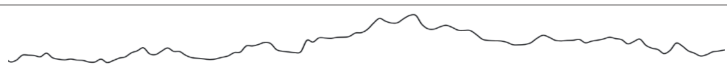
Material	Dry Density (g/cm^3)	Natural Density (g/cm^3)	Saturated Density (g/cm^3)	UCS (MPa)
Gypsum	0.83	1.15	1.40	2.95

3. Results

3.1 Surface Profile Reconstruction

Using the statistical reconstruction approach described in Section 2, ten representative profiles were successfully generated for each Joint Roughness Coefficient (JRC) range (Table 3). The reconstruction process employed random generations of ascent/descent sequences and climbing angles based on the measured mean and standard deviation values (Table 4). This process ensured that the reconstructed surfaces preserved the statistical properties of Barton's reference profiles while maintaining geometric variability. Representative reconstructed profiles for different JRC ranges are presented in Figure 6, demonstrating the feasibility of the reconstruction method.

Table 3. Reconstructed profiles for each Joint Roughness Coefficient (JRC) range.

No	Surface Roughness
1	
2	
3	
4	
5	
6	
7	
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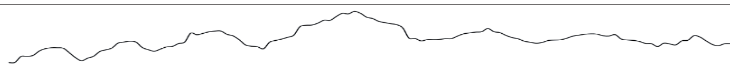
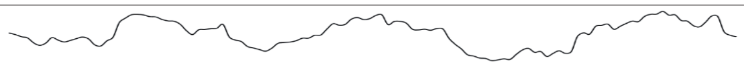
9	
10	

Table 4. Statistical parameters of the reconstructed profiles.

Note		Climbing Angle (θi)		Consecutive Ascend or Descend (Si)	
JRC	Profile	Mean (μ)	Standard Deviation (σ)	Mean (μ)	Standard Deviation (σ)
0 to 2	1	-0.85	9.80	-0.18	1.30
2 to 4	2	-0.08	9.86	-0.08	1.30
4 to 6	3	0.24	8.90	-0.03	1.35
6 to 8	4	0.52	14.03	-0.03	1.37
8 to 10	5	0.33	10.28	-0.10	1.90
10 to 12	6	-0.72	10.82	-0.34	3.43
12 to 14	7	0.41	15.77	0.02	1.82
14 to 16	8	0.73	16.61	0.28	2.36
16 to 18	9	1.30	17.70	0.26	2.38
18 to 20	10	-0.28	21.05	0.02	1.67

3.2 Sample Fabrication

The reconstructed profiles were successfully embedded into laboratory-scale specimens through 3D printing and gypsum casting, as described in Section 2. The resulting specimens exhibited well-defined shear surfaces corresponding to their respective JRC ranges (Figure 7). Visual inspection confirmed that the molds accurately transferred the geometric details of the reconstructed profiles into the specimens, enabling consistent sample preparation for shear testing.

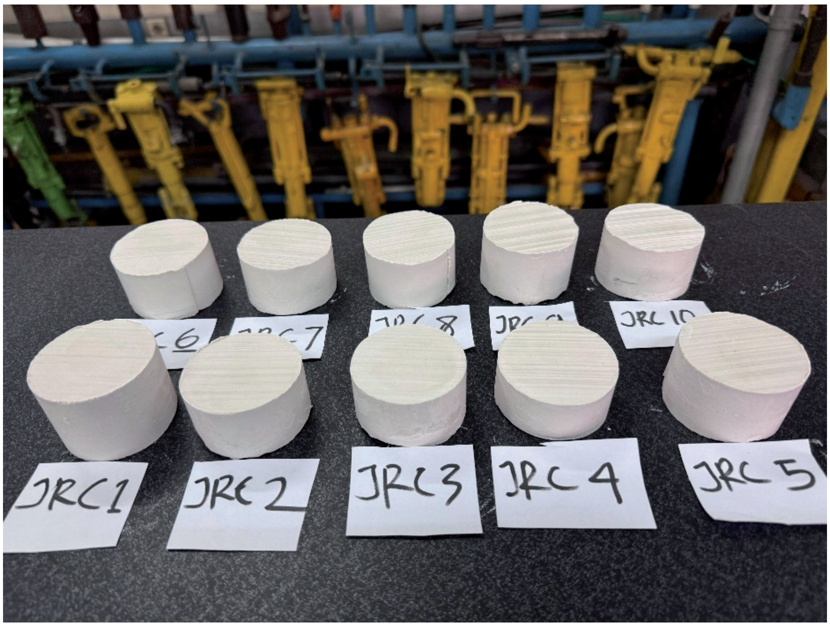


Figure 6. Laboratory specimen with a 3D-printed shear surface.

3.3 Direct Shear Testing

Direct shear tests were conducted on all reconstructed specimens. The results yielded distinct force–deformation responses for each JRC category. Typical force–displacement curves are presented in Figure 7, where specimens with higher JRC values generally demonstrated increased peak shear resistance compared to smoother profiles. This trend aligns with the expected influence of joint roughness on shear strength.

3.4 Shear Strength Parameters

From the shear test data, Mohr–Coulomb envelopes were derived for each reconstructed profile (Figure 8). The results show a clear correlation between increasing JRC and higher shear strength parameters (cohesion and friction angle). Table 6 summarizes the shear strength parameters obtained from all profiles. The data confirms that the reconstructed and 3D-printed specimens capture the essential relationship between joint roughness and shear strength, providing experimental validation for the feasibility of the proposed reconstruction and fabrication approach.

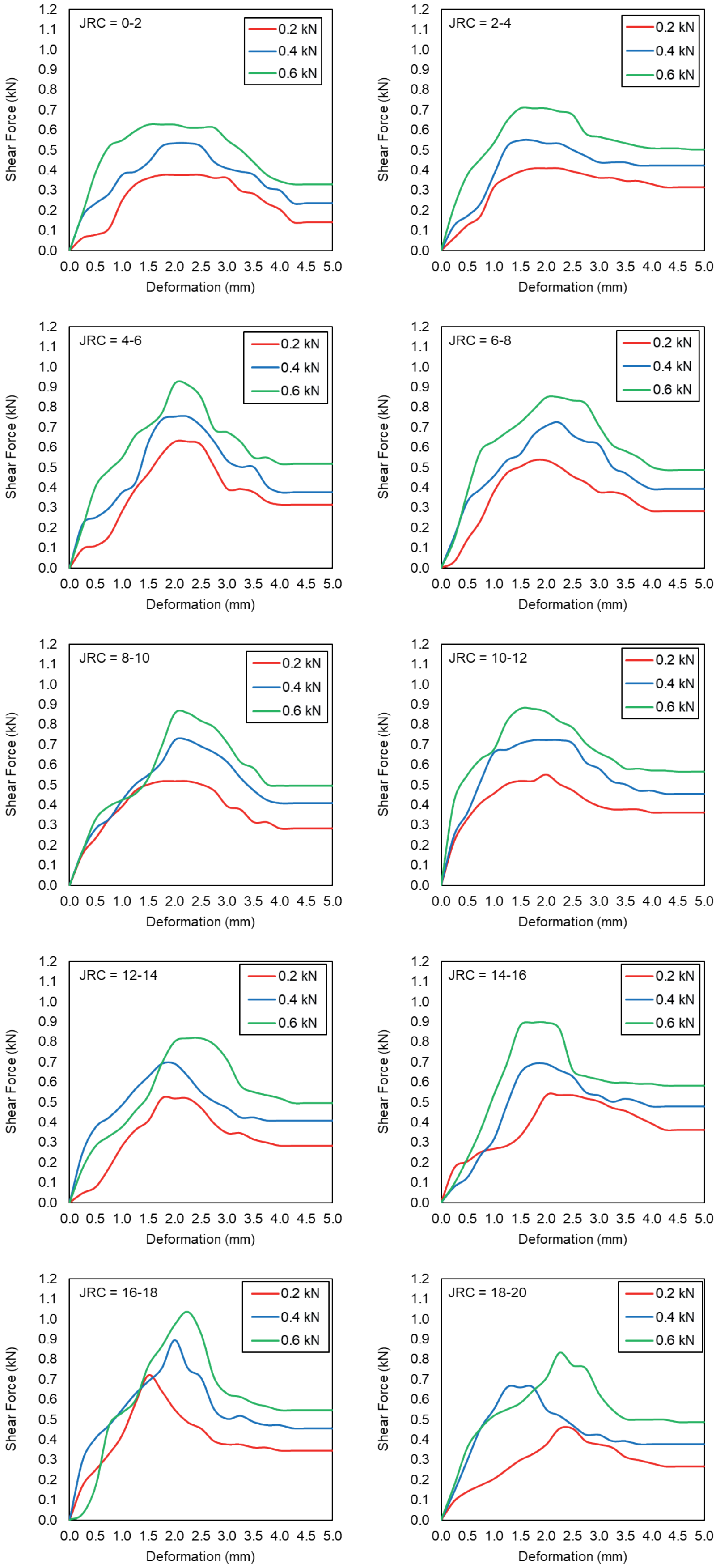


Figure 7. Force–displacement curves obtained from direct shear tests on reconstructed specimens.

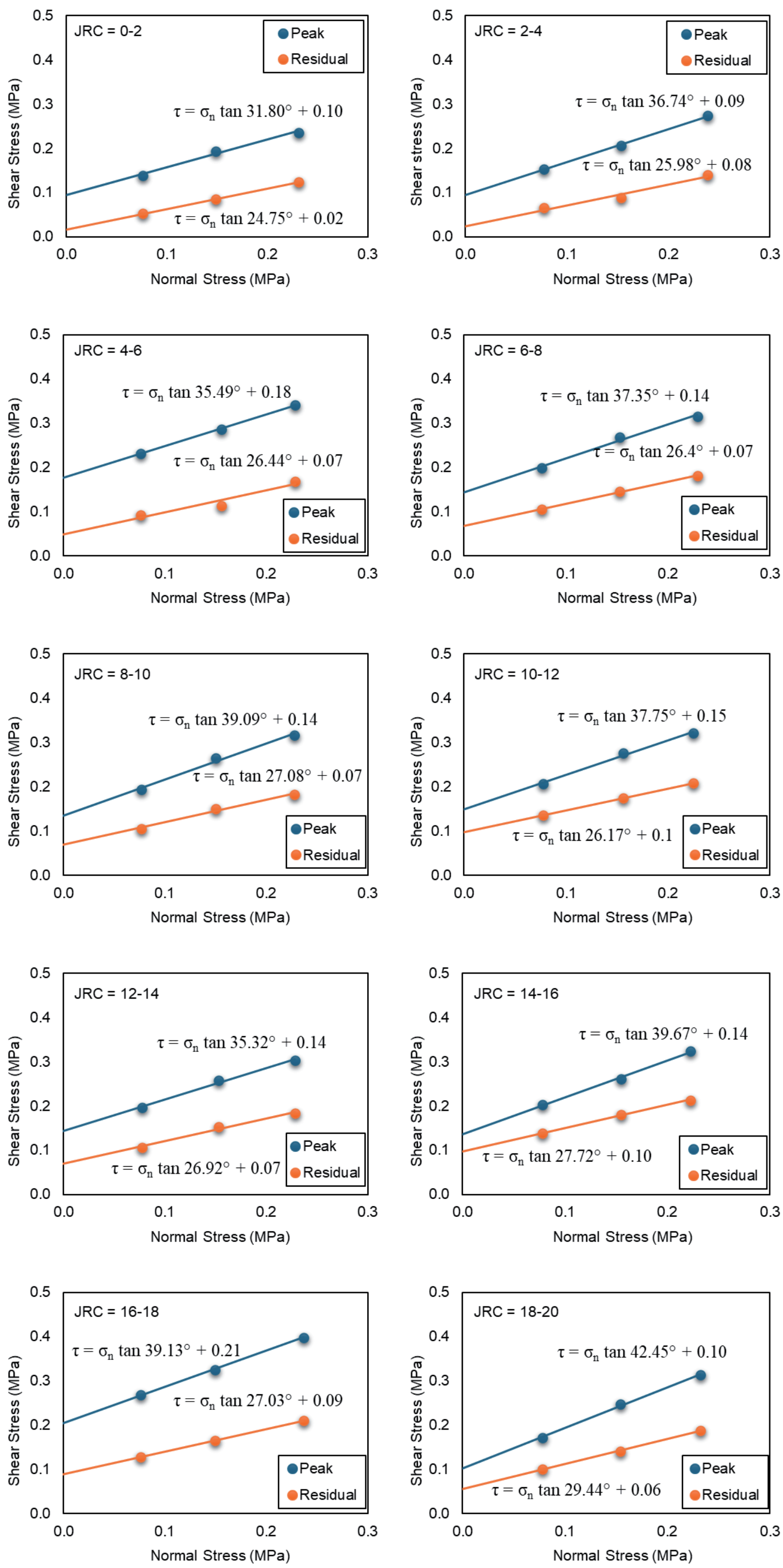


Figure 8. Mohr–Coulomb envelopes derived from direct shear test results of reconstructed specimens.

4. Discussion

Reliability of Surface Reconstruction

The reconstructed profiles demonstrated statistical properties that closely matched the reference datasets, confirming the robustness of the reconstruction method. While minor deviations were observed, such as in Profile 1, which exhibited a lower mean climbing angle compared to Profiles 2 and 3 despite having similar mean values and standard deviations of consecutive ascent/descent, these variations can be explained by the interaction between the underlying statistical parameters. Specifically, when the dataset has a negative mean for consecutive ascent/descent but a positive mean climbing angle, the reconstruction tends to generate more descending segments. This results in surfaces that appear rougher than expected. A similar pattern was observed for Profiles 9 and 10, suggesting that the stochastic generation process, while preserving statistical integrity, can produce geometrical outcomes that reflect subtle interactions between the two governing variables. Overall, the reconstructed surfaces can be considered successful representations of Barton's reference profiles, both visually and statistically.

Accuracy of Mold Fabrication

The fabrication process, using 3D-printed molds and gypsum casting, also proved successful, as evidenced by the well-defined shear surfaces embedded within the specimens (Figure 9). The 15-minute mold placement ensured sufficient curing time for accurate surface imprinting, and inspection confirmed that the transferred geometries were consistent with the reconstructed digital models. These results validate the feasibility of applying additive manufacturing techniques to reproduce joint roughness with satisfactory precision for laboratory testing.

Figure 9. Detailed picture of printed shear surface on sample.

Influence of Roughness on Shear Strength

The direct shear test results (Figure 8) demonstrate a clear relationship between surface roughness and shear resistance. In general, specimens with higher JRC values required greater shear force to mobilize deformation, reflecting the increased mechanical interlocking of rougher joint surfaces. This finding aligns with Barton's empirical observations and supports the hypothesis that joint roughness is a primary contributor to shear strength in rock masses.

Shear Strength Parameters and JRC Correlation

The derived Mohr–Coulomb envelopes (Figure 8) and subsequent parameter analysis (Figures 10–11) further illustrate the role of JRC in governing shear strength. The internal friction angle increased linearly with JRC, exhibiting a relatively high coefficient of determination (R^2), which confirms the predictive value of roughness in characterizing shear strength. The residual friction angle exhibited an even stronger correlation with JRC, suggesting that roughness effects persist even after peak shear strength is exceeded.

In contrast, cohesion displayed little to no meaningful correlation with JRC, as indicated by its low coefficient of determination. This outcome is consistent with expectations, since cohesion in the fabricated samples was negligible due to the pre-formed shear surfaces. In such cases, shear resistance is dominated by frictional and interlocking mechanisms rather than bonding forces, thereby reducing the apparent contribution of cohesion.

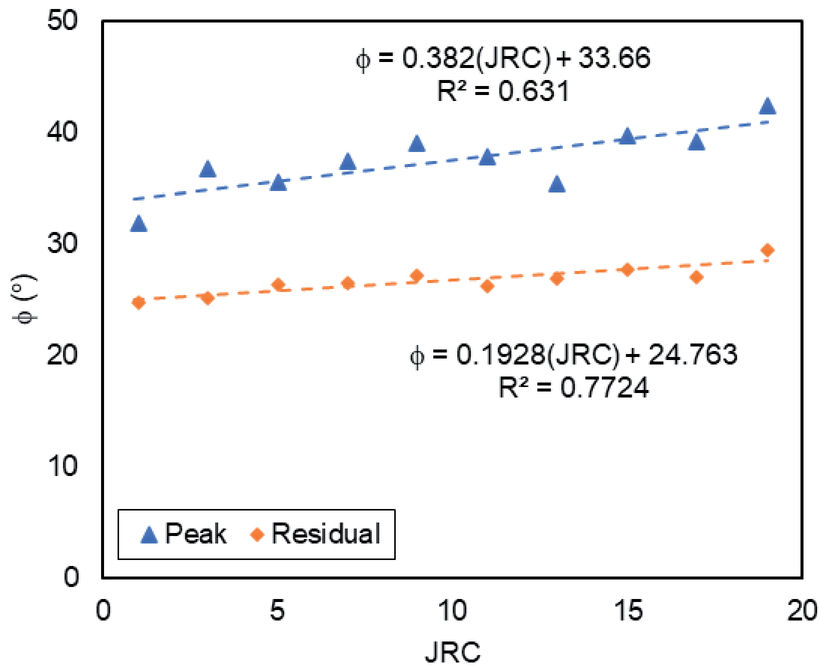


Figure 10. The relation between internal friction angle and JRC.

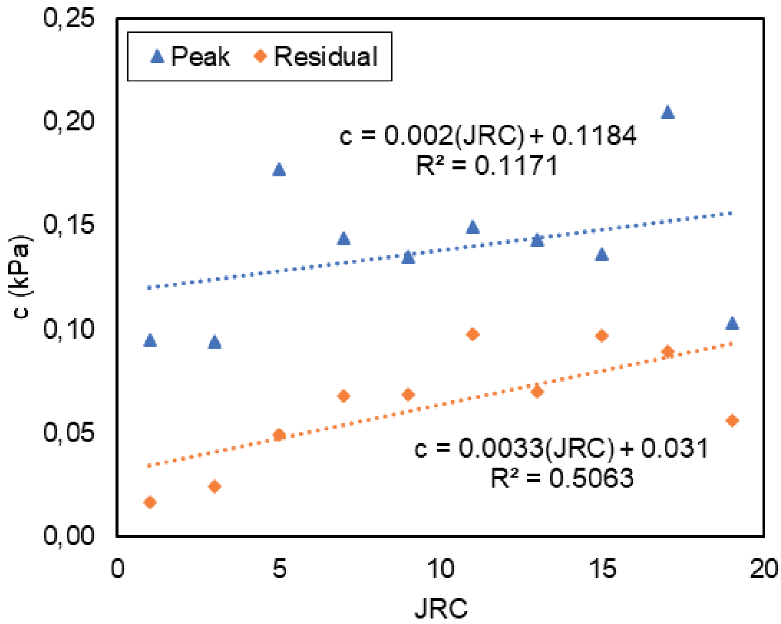


Figure 11. The relation between cohesion and JRC.

Implications and Limitations

These findings demonstrate that combining statistical reconstruction with 3D printing provides a viable framework for investigating the shear behavior of rock joints. The approach captures the essential influence of roughness on shear strength while offering reproducibility and control not always achievable in natural samples. However, the use of gypsum as a model material and the scale of laboratory testing may introduce limitations in directly extrapolating results to field conditions. Future studies should extend this method to alternative materials and larger-scale tests to further validate its applicability in rock engineering practice.

5. Conclusions

This study demonstrated the feasibility of reconstructing and fabricating rock joint shear surfaces based on statistical descriptors of roughness and reproducing them through 3D printing for laboratory shear testing. The main conclusions are as follows:

1. Surface reconstruction – The two-dimensional shear profiles of rock joints can be successfully reconstructed using the statistical approach proposed by Liu et al. (2022). The generated profiles closely replicate the statistical properties of Barton's reference roughness curves, validating the effectiveness of the reconstruction method.
2. Specimen fabrication – The use of 3D-printed molds combined with gypsum casting enables the preparation of laboratory specimens with pre-formed shear surfaces. These artificial joints reproduce the intended roughness geometry with good accuracy, providing a reproducible platform for experimental investigation. The prefabricated shear surfaces exhibit negligible cohesion, as the interface is deliberately formed to replicate joint separation, thereby making frictional resistance the dominant shear mechanism.
3. Shear strength parameters – Direct shear tests confirm that the internal friction angle increases with JRC. This relationship shows a strong linear trend, indicating that JRC can serve as a reliable empirical proxy for estimating the internal friction angle of rock joints. In contrast, cohesion shows little to no correlation with JRC, consistent with the pre-formed nature of artificial joints.

Overall, this research highlights the potential of combining statistical reconstruction with additive manufacturing to study the mechanical behavior of rock joints. The approach offers a controlled and reproducible means to investigate the influence of surface roughness on shear strength, and it may serve as a foundation for future studies exploring geomechanical processes in jointed rock masses.

Acknowledgments

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