J E M T
Journal of Earth and Marine Technology
homepage URL: ejurnal.itats.ac.id/jemt

Analyzing the roughness of the discontinuous surface in Mt. Semeru Eruption rock

Diana Irmawati Pradani[1], Heru Dwiriawan Sutoyo[2], Agus Suhardono[3],
Harsalim Aimunandar Jayaputra[4]
[1,3,4] Department of Civil Engineering, Politeknik Negeri Malang, Indonesia
[2] Departement of Mining Engineering, Institut Teknologi Yogyakarta, Indonesia
e-mail: dianapradani@polinema.ac.id

Article info
Received:
Feb 2, 2023
Revised:
Mar 10, 2023
Accepted:
Mar 23, 2023
Published:
Mar 31, 2023

Keywords:
Roughness, discontinuous, Joint Roughness Coefficient

Abstract
From the moment they were formed to the deposition process, the characteristics and properties of rocks that form on the earth's surface vary. The effects of Mount Semeru's eruption will be transported and deposited, eventually solidifying into rock masses. As a result of weak places like joints, fractures, and fissures, where the density, filling, and orientation are not continuous, rock masses in nature have discontinuous or discontinuous qualities. Rock shear strength will be decreased if there are discontinuous planes in the rock bulk. Using Barton's empirical equation and the Joint Roughness Coefficient (JRC) parameter, roughness conditions in discontinuous planes can be measured. Determining the features of the rock mass that are influenced by the shear strength of discontinuous planes in the Mount Semeru eruption rock based on variations in shear roughness in accordance with Barton and Choubey's criterion is therefore crucial. The observation of discontinuous plane roughness conditions in rocks as a result of Mount Semeru's eruption is necessary to get many rock shear strength parameters, which are then used to determine the friction angles, undulation values, and cohesion values in the surface of the discontinuous plane.

1. Introduction

Mt. Semeru, a stratovolcano with a characteristic Vulkanian-Strombolian eruption pattern, carries the potential for concurrent multiple eruptions. These eruptions can lead to the emission of diverse geological materials including bombs, lipari, lapilli, volcanic ash, and solid or liquid elements like lava [3]. Despite the destructive impact of Mt. Semeru's eruptions on the neighboring regions, the ejected rocks offer significant potential for reuse, especially in civil construction [4]. The Pronojiwo District in Lumajang Regency, which includes the Supiturang Village, was notably impacted by the Mt. Semeru eruption that occurred towards the end of 2021 [5]. The subsequent geological fallout was transported upstream along the river, thus providing opportunities for mining activities focused on stone and sand commodities [6].

The products of Mt. Semeru's eruptions are ultimately deposited and transform into rock masses [7]. These rock masses often exhibit discontinuous characteristics, presenting weak spots that lack consistent orientation [1]. Such discontinuities can influence the shear strength of the rock mass, often leading to a decrease in strength [2]. Therefore, it is crucial to investigate the properties of rock masses, specifically those influenced by the shear strength of discontinuous planes in rocks from the Mt. Semeru eruption. This involves analyzing variations in shear roughness in line with Barton and Choubey's criterion [8]. To accurately gauge the surface undulations of these discontinuous planes, we employed Barton's empirical equation, utilizing the Joint Roughness Coefficient (JRC) as a key parameter [9]. The JRC parameter was obtained from direct shear strength tests conducted in a laboratory setting [10]. For this study, we measured the surface roughness of the shear planes by directly observing the JRC values and comparing the roughness profiles based on variations in the shear surfaces' roughness, following Barton and Choubey's criteria [11].

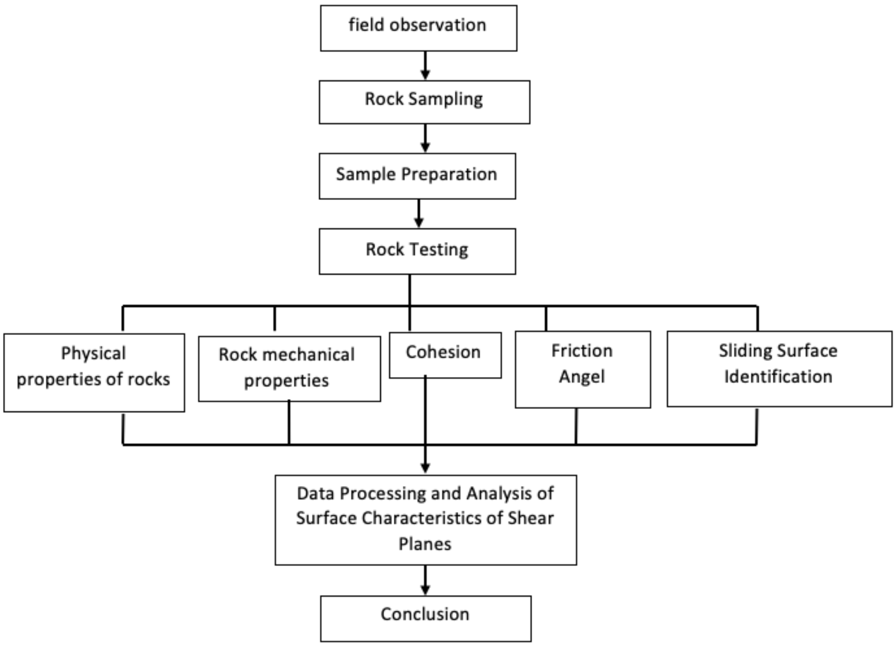


Figure 1. Research Flowchart

2. Methodology

The research was meticulously carried out in the well-equipped Mining Laboratory, housed within the Department of Civil Engineering at the State Polytechnic of Malang. The focal point of the study was the intriguing rocky remnants of Mount Semeru's eruption, serving as our primary sample material [3]. The study spanned a significant period from March 2nd to October 31st, 2022, a time devoted to the careful collection of rock samples [4], meticulous preparation, rigorous testing, and in-depth analysis of the resulting data[1, 12]. The primary variable under scrutiny was the intriguing surface roughness profile properties of the rocks birthed by Mount Semeru's eruption [8, 11].

We upheld the highest standards of scientific integrity throughout the research process[1,16], ensuring that the study unfolded in a transparent, methodical, and organized manner[15]. The research was conducted in progressive stages. Preparation Stage: This stage was marked by thorough readiness, where all necessary materials, data, and equipment were diligently assembled in advance[2, 18]. Testing Phase: This dynamic stage involved a series of tests starting with meticulous sample preparation[4], followed by comprehensive testing of physical attributes and shear strength[10, 13]. The objective was to obtain accurate measures of cohesion values, internal friction angles, shear strength values, and surface roughness profiles of shear planes[8, 9, 14]. Analysis and Discussion Stage: At this juncture, the research delved into discerning the shear plane's surface based on Barton and Choubey's criteria[8], supplemented by the outcomes of the tests conducted[11]. Conclusion Stage: This final stage involved synthesizing the debates and data analyses into a cogent conclusion, summarizing the study's findings[17, 19].

2.1. Characteristics of Rock Formations

The Earth's crust is predominantly composed of rock, a multifaceted substance exhibiting a vast array of properties, such as rock type, mineral composition, grain size, and structural formation [1]. Rock masses, often referred to as jointed rock masses, are naturally occurring aggregations of irregularly shaped, brittle rock fragments and interlocking blocks [2]. These individual components are separated by areas of weakness, including joints, faults, and bedding planes, which may contain softer materials [8,9,10,11]. Comprehensive understanding of rock formations is essential for accurately addressing geotechnical challenges [12,15,16]. Rock properties can be broadly classified into two categories: physical and mechanical characteristics [1,16]. Physical attributes encompass factors such as bulk density, porosity, water content, degree of saturation, and void ratio [1,16]. Mechanical properties include compressive strength, elastic modulus, Poisson's ratio, tensile strength, shear strength, cohesion, and internal friction angle [14,15,16,17,18].

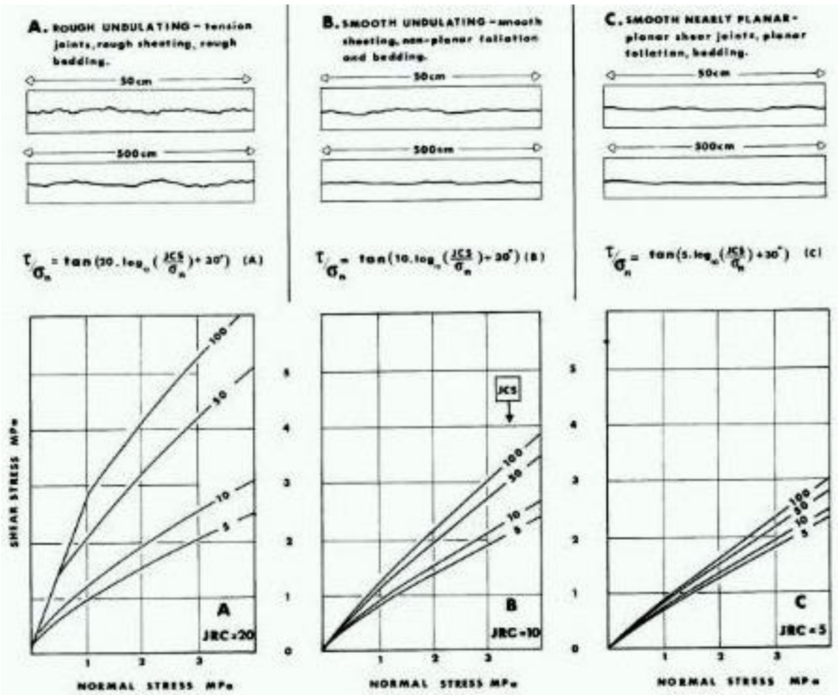


Figure 2. Classification of surface roughness of shear planes (ISRM 1981)

2.2. Categorizing Surface Roughness of Shear Planes

The examined rock from Mount Semeru presents a shear surface characterized by discontinuity and varying roughness. According to the International Society for Rock Mechanics (ISRM) 1981 standards, the shear plane's surface roughness is then classified into three categories: rough surfaces, smooth surfaces, and nearly planar smooth surfaces (refer to Figure 2) [15].

2.3. Understanding Rock Shear Strength

Astawa Rai et al. (2014) define rock shear strength as the rock's inherent resistance to the stress applied along its shear plane [25]. This resistance is a product of the interplay between the rock's intrinsic properties and external factors. Hoek and Bray (1981) noted that a rock mass contains discontinuous and weak sections, such as joints, faults, and bedding planes [12]. Deformations or collapses in intact rock and rock masses are primarily driven and regulated by the sliding plane within the discontinuous plane, especially in relatively shallow depths where operating stresses are minimal or absent. The physical characteristics of intact rock grains between the sliding planes could also be affected. Rock shear strength falls into two categories: peak shear strength and residual shear strength. Small displacements will trigger an elastic response in the rock (refer to Figure 3). This behavior is evidenced by a linear relationship between shear stress and displacement. The rock will progress through an elastic phase, plastic deformation, and finally fail when the applied force equals or surpasses the rock's peak shear strength. Following the failure, the shear stress required to shear the rock will decrease until it reaches a constant value, known as the residual rock strength. In ductile rocks, plastic deformation persists without a subsequent reduction in shear stress. The "Mohr-Coulomb Strength Line," drawn from direct shear strength test results under varying normal stress levels, illustrates the shear strength values at peak and residual conditions (refer to Figure 4).

The relationship between shear strength (τ) and normal stress (σ) can be represented by the Mohr-Coulomb equation: $\tau = c + \sigma \tan \phi$ (1) [27].

2.4. Criteria for Rock Shear Strength

Continuous data from testing or experimentation can be used to establish criteria for rock shear strength parameters. Under the assumption of plane strain or plane stress, these criteria yield a simple model incorporating one or more parameters of the rock's mechanical properties.

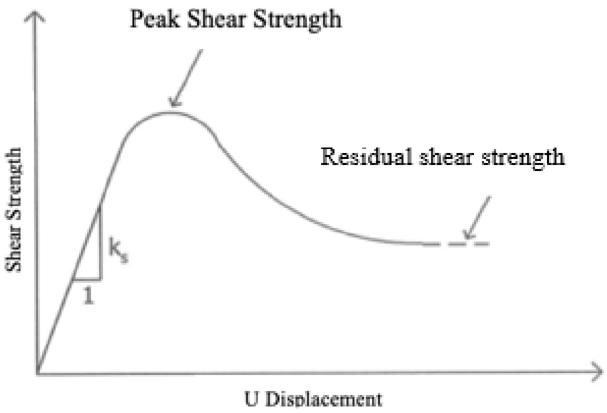


Figure 3. The stress yield curve and shear displacement with constant normal stress values [31]

2.4.1 Mohr–Coulomb Criterion

The shear strength criterion proposed by Coulomb in 1773 remains extensively applied [27]. According to Coulomb, the material's cohesion, along with a constant factor multiplied by the normal stress, could prevent failure along the shear surface plane. The Mohr-Coulomb equation has been referred to by various names. Initially, Anderson (1951) called it the Coulomb-Navier criterion, followed by Jaeger (1962) [9]. According to Navier, tan(ϕ) represents the dynamic friction coefficient, and c stands for plasticity. As the linear line on the Mohr strength envelope mirrors the linear line on the Coulomb criterion, other authors have termed it the Mohr-Coulomb criterion.

However, one must note the substantial differences between the Mohr and Coulomb criteria. Unlike Mohr's criterion (1900), which is illustrated by a concave downwards envelope and suggests that shear stress (τ) is a function of the normal stress (σ), Coulomb's criterion (1773) is a linear criterion. It explicates how the shear stress (τ) relies on σ, the inherent shear strength of the material, and a constant (ϕ), the internal friction coefficient [27]: $|\tau| = \tau o + \mu\sigma$ (2), $|\tau| = f(\sigma)$ (3)

2.4.2. Patton's Dilatance Criterion (Bilinear Curve)

Understanding the complex nature of discontinuous surface conditions is critical as it considerably influences the estimated shear strength of the rock mass. The previously discussed Mohr-Coulomb criterion applies to relatively flat shear surfaces. Patton [13] carried out a series of investigations to understand how shear surface roughness affects rock shear strength. The experiment was modeled using a sawtooth-shaped shear plane. As a rock moves over a rough surface, it experiences a volumetric increase, a phenomenon termed dilatation. This is due to the shear force (signified by y) acting in the direction of the slope angle i (first-order projection), lifting the upper block (see Figure 5). Assuming zero cohesion, equation (4) represents the shear stress (τm) acting in the direction i: $\tau m = \sigma m \tan \phi$ (4)

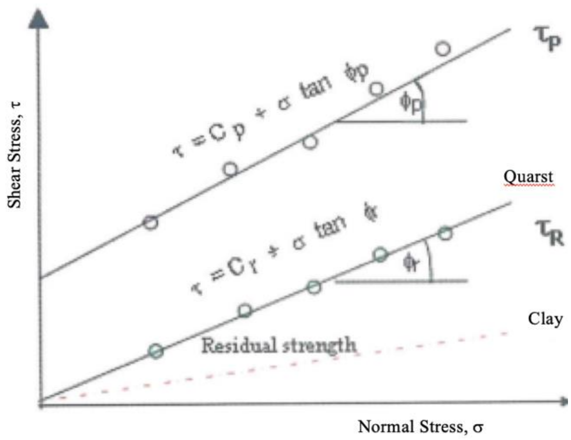


Figure 4. Mohr-Coulomb Strength Line (Astawai Rai, 2014)

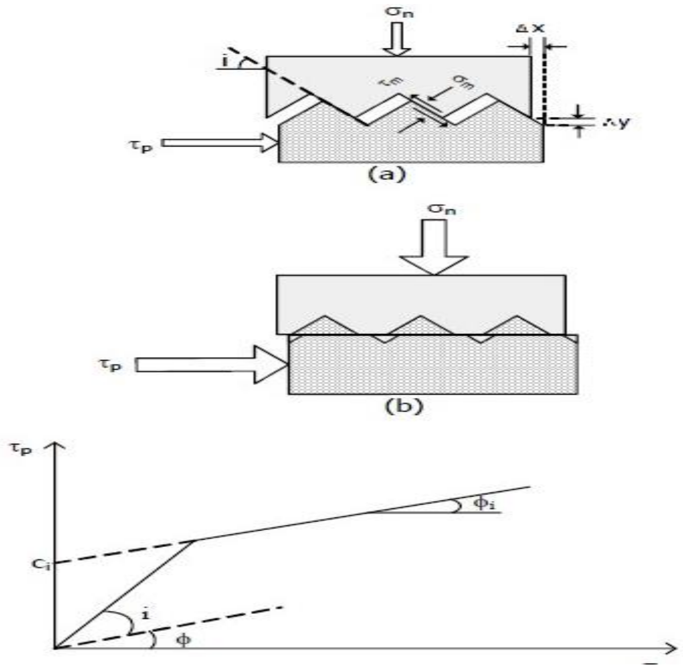


Figure 5. Shear roughness, (a) and (b) failure mechanism, (c) strength sheath [27]

2.4.3. Barton and Choubey Criteria

Barton and Choubey [8][9] proposed an alternative method for estimating the shear strength of discontinuous surfaces with rough textures. They suggested that basic criteria such as those of Mohr-Coulomb or Patton [13] were inadequate to explain rock shear strength. Barton's research introduced an additional parameter referred to as artificial strength, leading to equation (5):

$\tau = \sigma n \tan \{ \phi b + JRC \log (JCS / \sigma n) \}$ (5)

Where:
JRC = Joint Roughness Coefficient or surface roughness coefficient
JCS = Joint Wall Compressive Strength or uniaxial compressive strength value of the filling material
ϕb = base friction angle

Barton and Bandis [14] also provided a formula for correcting the JRC scale for sample sizes larger than 100mm, as shown in equation (6): $JRCn = JRC0[Ln/L0]-0.02\ JRC0$ (6)

Where:
JRC = Joint Roughness Coefficient or surface roughness coefficient
JCS = Joint Wall Compressive Strength or uniaxial compressive strength value of the filling material
JRC0 = Coefficient of roughness observed at a laboratory scale
JRCn = Actual roughness coefficient
Lo = Standard test sample size for the 100 mm Barton test
Ln = Actual test sample size
ϕb = base friction angle
σn = normal stress (normal stress)

There are two methods to determine the value of JRC. The first is a visual estimation compared to the roughness section from shear strength test results obtained at a laboratory scale. The second method involves field-based direct measurement techniques supplemented by empirical analysis reference data (see Figure 6).

2.4.4. Joint Roughness Conditions (Joint Roughness)

Stubborn Roughness is the condition of joint roughness is determined by several parameters, including surface irregularities, separation between surfaces, length of the joint, weathering of rock walls, and filling material. Roughness can be defined as the extent of surface irregularities on a joint surface, which acts as an interlock to prevent displacement along the joint surface [19].

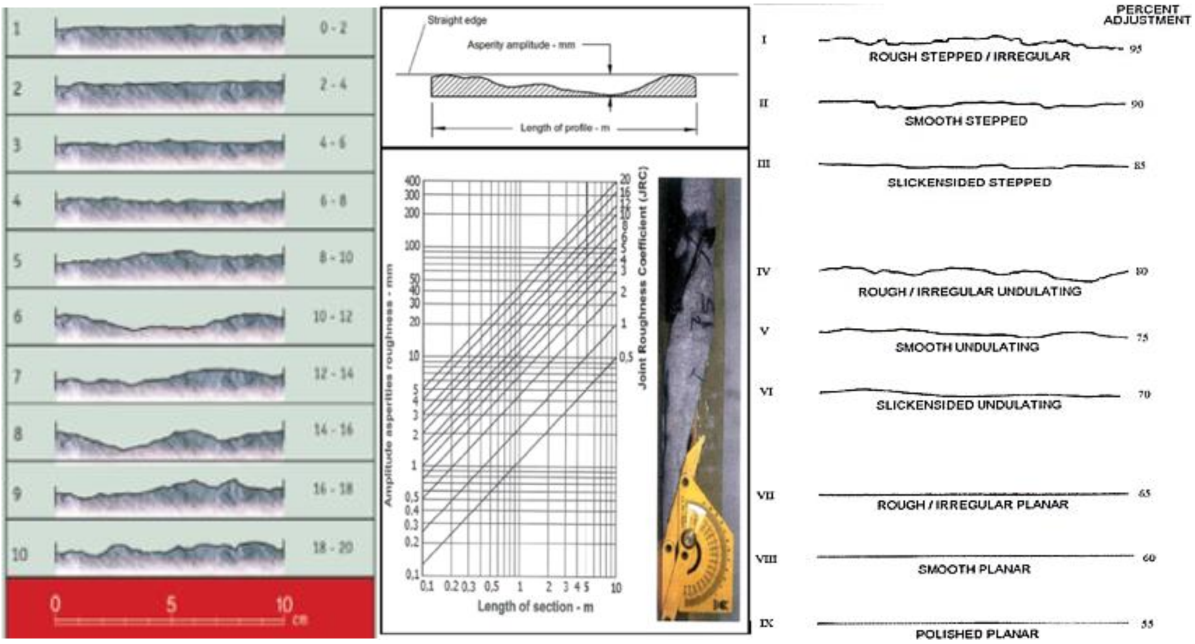


Figure 6. Roughness level profile for JRC Joint Roughness Coefficient range values [8] (left and middle), Profile of joint face roughness [15] (right).

The robust Roughness Profile on a joint plane is described using the reference provided by ISRM (1981) [15] as depicted in Figures 6 right and 7. The profile length in the reference is typically 1-10 meters, with the vertical and horizontal scales being the same. The roughness conditions, representing the reference joint surfaces, can be categorized as follows:

Very rough: When the surface of the joint plane exhibits nearly vertical irregularities.
Rough: When the roughness is clearly visible and can be felt slightly abrasive to the touch.
Low roughness: When the roughness on the joint surface can only be detected by touch.
Smooth: When the rough surface becomes relatively smooth to the touch.
Slippery: When the rough surface appears wavy but with a smooth texture.

According to Hudson and Harrison (1997) [16], although the direction and persistence of a discontinuity plane are considered planar, the surface may exhibit unevenness. Giani (1992) [17] stated that the roughness parameter accounts for unevenness, which causes wavy discontinuities. Large undulations describe wavy discontinuities, while small-scale roughness characterizes uneven discontinuities. The discontinuity surface may have a rough or smooth appearance depending on the degree of undulation or planarity [17].

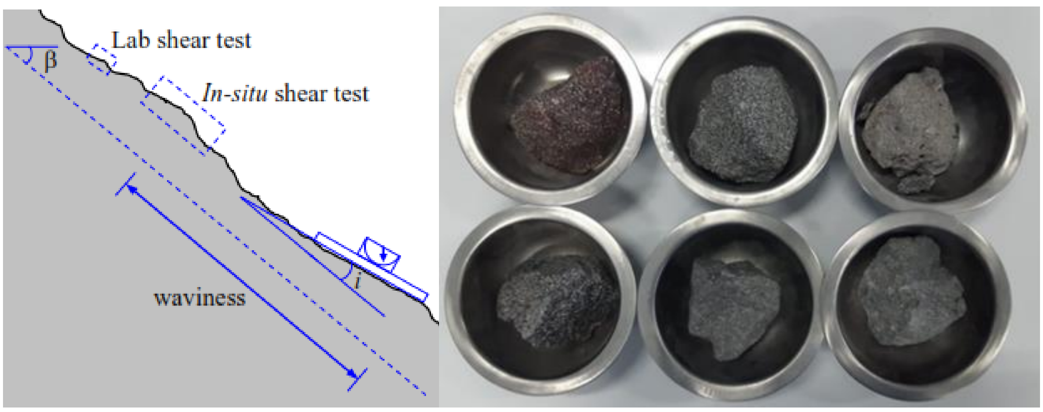


Figure 7. The results of the reference comparison of roughness scale reviews conducted in the field and laboratory [15] (left), the rock samples (right).

Table 1. Rock Physical Properties Testing Results

Parameter	Sample						Average
	1	2	3	4	5	6	
Natural Density (gr/cm^3)	1.89	1.92	2.09	2.15	1.39	1.87	1.89
Dry Density (gr/cm^3)	1.87	1.92	2.07	2.14	1.38	1.86	1.87
Saturated Density (gr/cm^3)	1.98	2.01	2.10	2.17	1.43	1.98	1.94
Apparent Specific Gravity	2.18	2.19	2.13	2.21	1.48	2.23	2.07
True Specific Gravity	2.11	2.10	2.13	2.21	1.45	2.11	2.02
Natural Water Content (%)	1.08	0.24	0.73	0.54	0.69	0.28	0.59
Absorption (%)	5.97	4.57	1.35	1.41	3.27	6.32	3.81
Saturated Degree (%)	18.10	5.15	54.05	38.64	21.26	4.46	23.61
Porositas (%)	11.17	8.77	2.80	3.01	4.51	11.79	7.01
Void ratio	0.13	0.10	0.03	0.03	0.05	0.13	0.08

Giani (1992) [17] also mentioned that the roughness profile of a discontinuity can be observed along an axis, representing the potential direction of discontinuity plane displacement. Measurement methods can be applied using various scales, ranging from outcrop-scale observations in the field to the smallest scale examined in laboratory tests. Hudson and Harrison (1997) [16] conducted roughness measurements utilizing standard charts and mathematical formulations. In the initial investigation stage, a visual assessment of roughness is typically performed, using the Joint Roughness Coefficient (JRC) developed by Barton (1973) [9].

The differences in roughness between joints or discontinuity planes can be compared on different scales, such as intact rock and rock mass scales, as described by ISRM (1981) [15]. The intact rock scale is generally associated with shear strength tests conducted in the laboratory, while shear strength tests performed in situ represent rock mass conditions. Wyllie and Mah (2004) [18] explained that the JRC value can be visually determined by comparing the surface conditions to a standard profile based on a combination of centimeter-scale irregularities and meter-scale undulations. The JRC values proposed by Barton (1973) [9] range from five for planar joints to twenty for coarse undulating joints. These values are subjective estimates based on comparisons with standard roughness profiles [18].

3. Results and discussion

3.1. Rock Sample Testing

At the State Polytechnic of Malang's Mining Laboratory, which is part of the Department of Civil Engineering, a comprehensive testing program was conducted on the rock samples collected from the Mount Semeru eruption in Lumajang Regency, East Java. The objective was to assess various properties and characteristics of the rocks (Figure 8) [22]. The testing included the analysis of physical properties, the point load index test, and the digitization of surface roughness using a profilometer.

Table 2. Rock Point Load Test Results

Parameter	Sample	
	Unexposed	Exposed
Point Load Test (kN)	6.42	5.86
De^2	71.17	57.19
De	8.44	7.56
F	0.45	0.43
IS (N/cm^2)	40.48	43.81
UCS (MPa)	11.66	12.62

Table 3. The roughness angle profile results (left). **Table 4.** The shear strength parameter results (right)

Ordo	Angle
i_I	47^0
i_{II-1}	50^0
i_{II-2}	36^0
i_{II-3}	52^0

Condition	Normal Strength (KPa)	Shear Strength (KPa)	Cohesi (KPa)	Friction Angle (…^{0})
Exposed	3786	7355,85	2510	52
Unexposed	3498	5704,14	1953	47

3.2. Physical Properties Test

To gain a deeper understanding of the rock samples, a range of physical properties tests were performed. The apparent specific gravity, natural density, dry density, and saturated density of the rocks were determined. Table 1 presents the results of these tests, encompassing specific gravity, real specific gravity, natural water content, rock saturation (absorption), saturation level, porosity (n), and void ratio (e) [22]. These parameters provide valuable insights into the density and water-holding capacity of the rocks, which are crucial factors in evaluating their mechanical behavior.

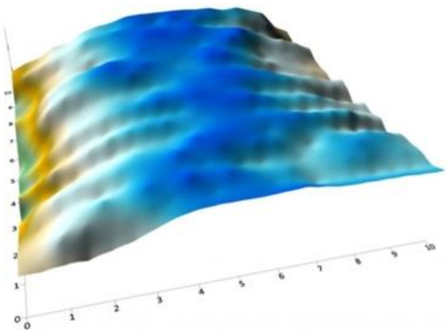
3.3. Rock Point Load Test

The point load index test was employed to estimate the compressive strength or UCS (Uniaxial Compressive Strength) value of the rocks. This test is widely used in the field as it provides a quick estimation of rock strength before more detailed laboratory testing. The simplicity and portability of the test apparatus allow for rapid determination of the point load index, which serves as an initial indicator of rock strength [23]. Table 2 summarizes the point load index values obtained from the tests.

3.4. Digitizing Rock Roughness

In order to analyze the roughness characteristics of the rock surfaces, the digitization of surface roughness was conducted. Both the exposed and non-exposed surfaces of the rock samples were utilized for this purpose (Figure 9) [30]. A profilometer was employed to capture the surface roughness profile, providing quantitative data on the roughness magnitude and profile shape. The collected data was then processed to generate the roughness contour of the rock surfaces, enabling a detailed assessment of their roughness characteristics.

Based on the roughness profiles and the reference provided by ISRM (1981) [15], the rocks formed by the Mount Semeru eruption exhibited varying levels of roughness. The Joint Roughness Coefficient (JRC) values for the rocks ranged from 10 to 12, indicating smooth undulating surfaces (Figure 11). However, the exposed rocks resulting from the eruption displayed higher JRC values, ranging between 18 and 20, classifying them as rough/irregular undulating surfaces based on the ISRM classification [15]. These findings highlight the significant influence of surface roughness on the mechanical behavior of the rocks and emphasize the need to consider roughness parameters in rock engineering analysis.



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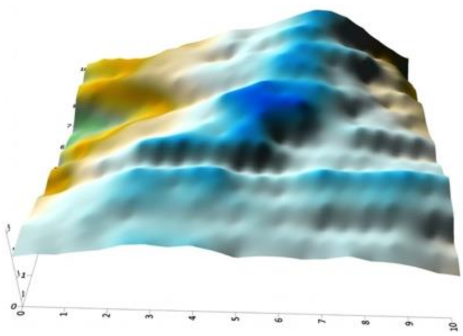

Figure 9. The results of Exposed Rock Roughness Digitization (left), Unexposed Rock Rough Digitization Results (right).

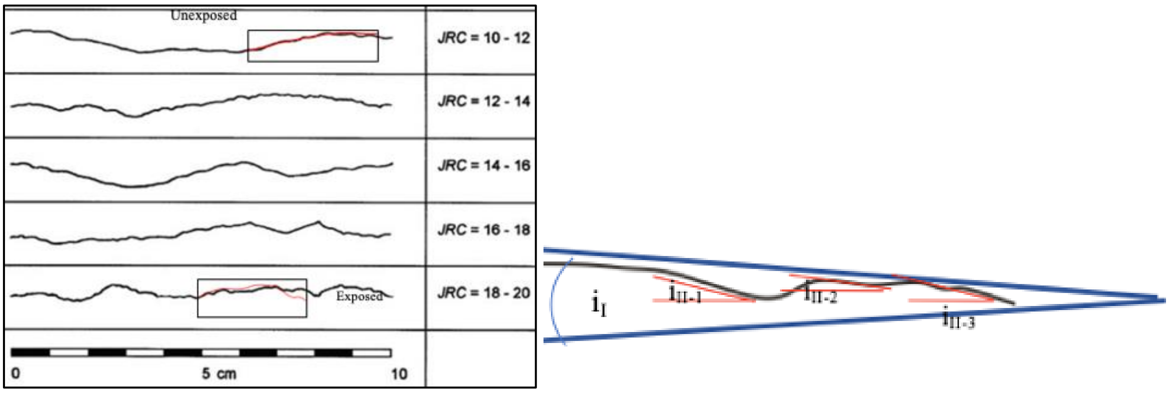

Figure 10. Roughness profile interpretation results (left), the plane surface roughness angle (right)

The analysis of the point load test results revealed distinctive variations in the point load index values between the exposed and non-exposed rocks. Further evaluation of the data enabled the determination of shear strength parameters for each rock condition. Figure 10 right and Table 3 present the variations in cohesion, plane roughness coefficient, and internal friction angle associated with the surface roughness of the rocks formed by the Mount Semeru eruption. Notably, the cohesiveness value (c) and internal friction angle (ϕ) exhibited an increasing trend as the angle created by the surface roughness wave of the shear plane increased (Figure 11 and Table 4). These observations demonstrate the influence of surface roughness on the shear strength characteristics of the rocks.

In conclusion, the comprehensive testing program conducted on the rock samples from the Mount Semeru eruption provided valuable insights into their physical properties, point load index values, and surface roughness characteristics. The obtained results contribute to a better understanding of the mechanical behavior and strength parameters of pyroclastic rocks, which are essential in the field of rock mechanics and rock engineering. These findings lay the foundation for further research and analysis, enabling the development of effective rock engineering strategies for geological hazard mitigation, infrastructure design, and mining operations.

4. Conclusion

The analysis of the rock samples from the Mount Semeru eruption in Lumajang Regency, East Java, has provided valuable insights into their surface roughness characteristics and mechanical behavior. Based on the JRC (Joint Roughness Coefficient) values obtained from the roughness profile analysis and the references provided by ISRM (1981) [15], it was determined that the rocks can be classified into different roughness categories. The JRC values ranged from 10 to 12, indicating smooth undulating surfaces, falling under category V [15]. However, the exposed rocks resulting from the eruption exhibited higher JRC values ranging from 18 to 20, classifying them as rough/irregular undulating surfaces, falling under category IV according to ISRM [15]. This emphasizes the significance of surface roughness in characterizing the rock's behavior.

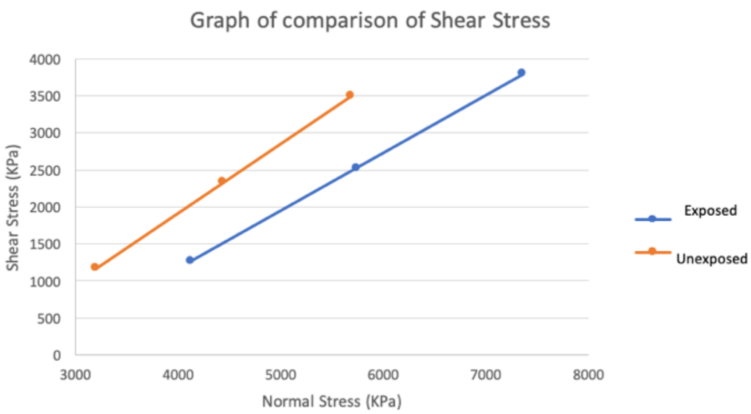

Figure 11. Graph of Comparison of Shear Stresses of Mount Semeru Rocks

The digitization of surface roughness profiles allowed for a comprehensive evaluation of the roughness changes in the rocks. The results confirmed that the JRC value can be utilized as a metric to assess variations in the roughness profile of rocks, providing valuable information for rock engineering applications. Furthermore, the study found that the shear stress values differed between the exposed and unexposed rocks. A regression equation analysis revealed that the unexposed rocks exhibited higher shear stress values compared to the exposed rocks. Additionally, the values of cohesion and internal shear angle were found to have a significant influence on the rock behavior under both conditions. The exposed rocks, despite their relatively high degree of roughness, exhibited lower shear strength compared to the unexposed rocks, as inferred from the shear stress equation and calculations of roughness profiles.

In conclusion, the findings of this study contribute to a better understanding of the surface roughness characteristics and mechanical behavior of rocks from the Mount Semeru eruption. These insights are crucial for various engineering applications, such as geological hazard assessment, infrastructure design, and mining operations, enabling more accurate and informed decision-making processes.

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