

Article

Shear Mechanical Behavior of Lunar Regolith Simulant with Different Relative Densities Under Thermal–Mechanical Coupling

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Abstract

The mechanical behavior of lunar regolith is crucial for lunar exploration projects, particularly drilling and sampling equipment. However, the extremely limited quantity of returned lunar regolith is insufficient for systematic macroscopic mechanical testing. Lunar regolith simulants are therefore widely used to investigate the macroscopic mechanical behavior of lunar regolith. Most previous studies were conducted under ambient laboratory conditions, with limited consideration of temperature effects. In this study, direct shear tests were conducted on lunar regolith simulant specimens with relative densities D_r of 75%, 90%, and 100% under normal stresses of 50, 100, and 150 kPa and at temperatures of 25, 60, 120 and 180 °C. The effects of relative density, normal stress, and temperature on the shear response were systematically evaluated. The results showed that the peak and residual shear strengths generally increased with normal stress, whereas the effect of temperature on peak strength depended on relative density and normal stress. Three-dimensional laser scanning was used to reconstruct and quantitatively characterize the post-shear surface morphology, and its relationship with the measured shear response was examined. A damage-based phenomenological formulation incorporating a log-logistic function was used to parameterize the shear stress–displacement responses and to examine the fitted shear-stiffness parameter and phenomenological damage variable. The implications of the measured shear behavior for lunar drilling and sampling were also discussed. The study can provide laboratory-scale insights into the shear behavior of lunar regolith simulant relevant to lunar drilling and sampling.

Keywords: lunar regolith simulant; temperature; thermo-mechanical coupling; shear behavior; shear surface morphology



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1. Introduction

The Moon harbors abundant material resources, such as minerals, water ice and volatiles, which serve as a significant supplement to Earth's resources [1–3]. Among them,

the reserve of ^3He on lunar regolith is approximately 1.03~1.29 million tons, which is more than 50,000 times the reserve on Earth [4]. Once developed and utilized, it could sufficiently supply Earth's clean energy needs on a ten-thousand-year scale. Resource extraction from the Moon has become a key strategy for Earth's sustainable development [5]. In recent years, major spacefaring powers have launched new lunar exploration programs to develop and utilize lunar resources, including the United States' Artemis program, Russia's Luna series of missions, and China's Chang'E Phase IV Project. These lunar exploration programs focus on the utilization of lunar resources, and involve multiple critical engineering challenges, such as lunar drilling and sampling, as well as the construction of lunar bases [6]. Lunar regolith, the most abundant material on the lunar surface, is the foremost research focus of the aforementioned lunar exploration programs. Therefore, a deep understanding of the mechanical behavior of lunar regolith under various boundary conditions is crucial for the successful execution of lunar exploration missions in the future [7].

Following the Apollo missions, the mechanical behavior of returned lunar regolith was investigated through triaxial [8] and direct shear tests [9,10], providing early estimates of its compressibility, cohesion, and internal friction angle. However, the limited quantity of returned lunar regolith precludes extensive macroscopic mechanical testing. Lunar regolith simulants are therefore widely used for systematic laboratory investigations [11,12]. Using data from lunar missions and laboratory measurements of returned lunar samples, research institutions worldwide have developed several lunar regolith simulants, including JSC [13] and MLS [14] in the United States, and WHU-1 [15], CAS-1 [16], and QH-E [17] in China. Extensive studies on the mechanical properties of these lunar regolith simulants have also been conducted. The mechanical behavior of these simulants has subsequently been investigated using triaxial [18,19], tensile [20], and direct shear tests [21]. Zou et al. [22] and Li et al. [23] studied the triaxial mechanical behavior of QH-E lunar regolith simulant through laboratory experiments and discrete element simulations, comparing strain softening and dilation responses at different stress levels. Zhang et al. [24] conducted direct shear, compression, and triaxial tests on CAS-1 lunar regolith simulant, investigating the stress–strain curve and shear strength properties. Jiang et al. [25] and Lin et al. [26] investigated the shear behavior of TJ-1 lunar regolith simulant and reported that strain softening became more pronounced with increasing relative compaction. Collectively, these studies indicate that the initial particle-packing state and stress level strongly influence the strength and deformation behavior of lunar regolith simulants. Melzer et al. [27] reported that the internal friction angle decreased with increasing confining pressure, with a greater reduction observed in more densely compacted specimens. This stress dependence may be associated with particle breakage induced by increased confinement and accumulated shear deformation. Breakage of angular particles and surface asperities reduces particle angularity, mechanical interlocking, and dilatancy, while shifting the dominant contact mechanism toward frictional sliding. Consequently, the mobilized peak friction angle may decrease with increasing confining pressure. Huang et al. [28] further showed that the shear strength of lunar regolith simulant was sensitive to the applied stress state. In addition, in situ measurements indicate that the bulk density of lunar regolith generally increases with depth, reflecting progressive densification [29]. This depth-dependent densification can influence the mechanical response of regolith at different depths. However, research on the direct shear behavior of lunar regolith simulants at different relative densities remains limited, restricting a comprehensive understanding of how the particle-packing state affects shear response under conditions relevant to lunar drilling and sampling.

Researchers have also investigated lunar regolith simulants from mesoscopic and microscopic perspectives. Rame et al. [30] examined the frictional contribution to the shear strength of JSC-1, while Nie et al. [31] proposed a cross-scale approach for predicting

residual friction angle from particle-scale information. Other studies have examined the effects of reduced gravity [32,33], surface cleanliness [34], particle-size distribution [35], van der Waals forces [36], and particle shape [37,38]. These investigations have improved understanding of the factors controlling regolith mechanical behavior. However, most previous mechanical tests were conducted near room temperature, and the temperature dependence of the shear behavior of lunar regolith simulants remains poorly constrained. Lunar regolith experiences substantial temperature variations with location, illumination conditions, and depth. Temperature should therefore be considered when evaluating regolith mechanical behavior under lunar-relevant conditions [39,40].

In the context of lunar resource exploration and utilization, reliable characterization of regolith mechanical behavior is relevant to engineering operations involving excavation, sampling, and drilling [41]. Rotary drilling is an important approach for lunar subsurface sampling [42,43]. During drilling-based sampling, the interaction between the drill bit and regolith involves localized cutting and shearing of the granular material [44], accompanied by particle rearrangement and frictional resistance. The shear response of regolith therefore represents an important mechanical component of tool–regolith interaction. Accordingly, clarifying how particle-packing state, stress level, and temperature affect regolith shear behavior is important for establishing a laboratory-scale mechanical basis for understanding regolith response during lunar drilling and sampling. In summary, lunar regolith exhibits spatial and depth-dependent variations in density and thermal conditions. However, the coupled effects of relative density, normal stress, and temperature on its direct shear response remain insufficiently characterized.

In this study, direct shear tests were conducted on a lunar regolith simulant at different relative densities, normal stresses, and temperatures to quantify their effects on shear strength and post-peak response. A damage-based phenomenological formulation incorporating a log-logistic function was used to parameterize the measured shear stress–displacement responses and examine the fitted shear-stiffness parameter and phenomenological damage variable. The exposed post-shear surfaces were reconstructed using three-dimensional laser scanning, and their morphological characteristics were quantified and related to the measured shear responses. Finally, the relevance and limitations of the experimental results for lunar drilling and sampling were discussed.

2. Methods

2.1. Basic Characteristics of Lunar Regolith Simulant

The lunar regolith simulant used in this study was prepared and provided by the China Academy of Space Technology, Beijing, China and consists of approximately 80% Cenozoic alkaline olivine basalt and 20% plagioclase. Its mineralogical and chemical compositions were designed to approximate those of lunar regolith (Figure 1a). The raw materials were dried, crushed, ground, sieved, and proportionally blended, and the 0–2 mm particle-size fraction was used for specimen preparation. The particle-size distribution of the simulant falls within the range reported for lunar regolith (Figure 1b). Scios 2 scanning electron microscopy (Thermo Fisher Scientific, Hillsboro, OR, USA) was used to characterize particle morphology (Figure 1c). The particles are highly irregular and angular, with sharp edges and surface asperities broadly resembling the morphology reported for actual lunar regolith particles (Figure 1d).

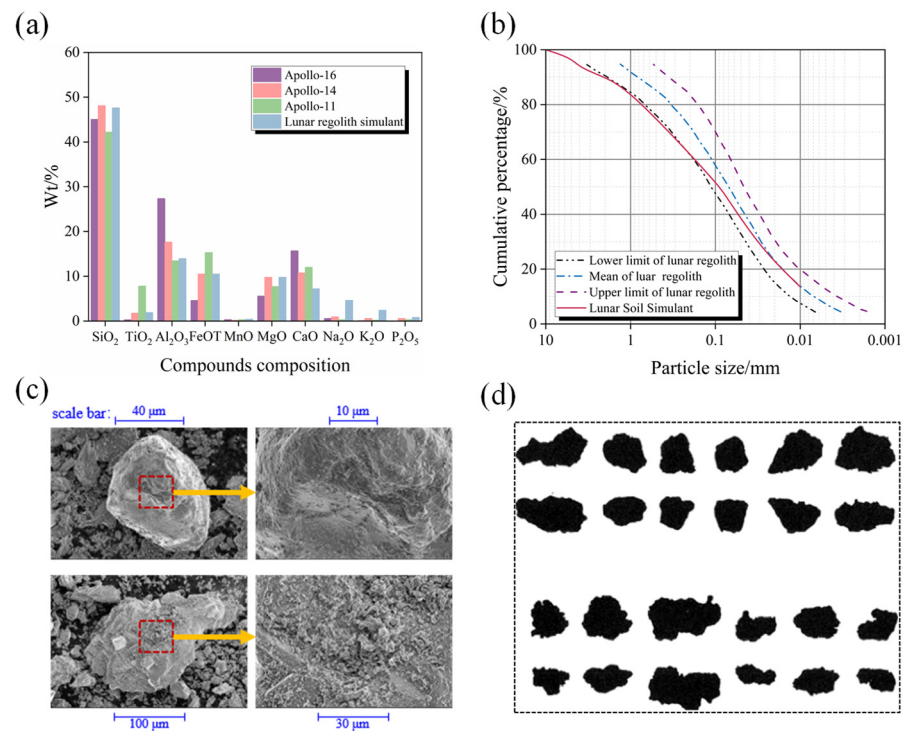


Figure 1. Physical and compositional characteristics of the lunar regolith simulant. (a) Major chemical composition; (b) particle-size distribution; (c) SEM images of simulant particles; (d) typical particle morphology of actual lunar regolith [33,45].

2.2. Specimen Preparation and Test Program

Before specimen preparation, the simulant was oven-dried at 105 °C for 24 h. The change in mass became negligible after 24 h, indicating that most free water had been removed (Figure 2a). The dried material was then cooled to room temperature in a sealed container to minimize moisture uptake. The maximum and minimum dry densities, determined using vibratory compaction and funnel deposition, were 2.024 and 1.331 g/cm³, respectively. The relative density was calculated as,

$$D_r = \frac{(\rho - \rho_{min})\rho_{max}}{(\rho_{max} - \rho_{min})\rho} \times 100\% \quad (1)$$

where ρ , ρ_{max} , and ρ_{min} denote the current dry density, maximum dry density, and minimum dry density of the specimen, respectively. The target dry densities corresponding to D_r values of 75%, 90%, and 100% were 1.791 g/cm³, 1.924 g/cm³, and 2.024 g/cm³, respectively. Cubic specimens (70 × 70 × 70 mm) were prepared directly in the shear box in three equal-mass layers:

- (1) For each target relative density, the required dry mass was calculated from the target dry density and specimen volume and divided into three equal portions.
- (2) Each portion was deposited through a funnel whose outlet was kept close to the deposition surface and moved uniformly across the shear-box area. The material was then leveled and brought to the prescribed layer height using a custom-made rammer.
- (3) Before the subsequent layer was placed, the surfaces of the first and second layers were lightly roughened with a brush. After placement of the third layer, the specimen surface was leveled to the prescribed height.

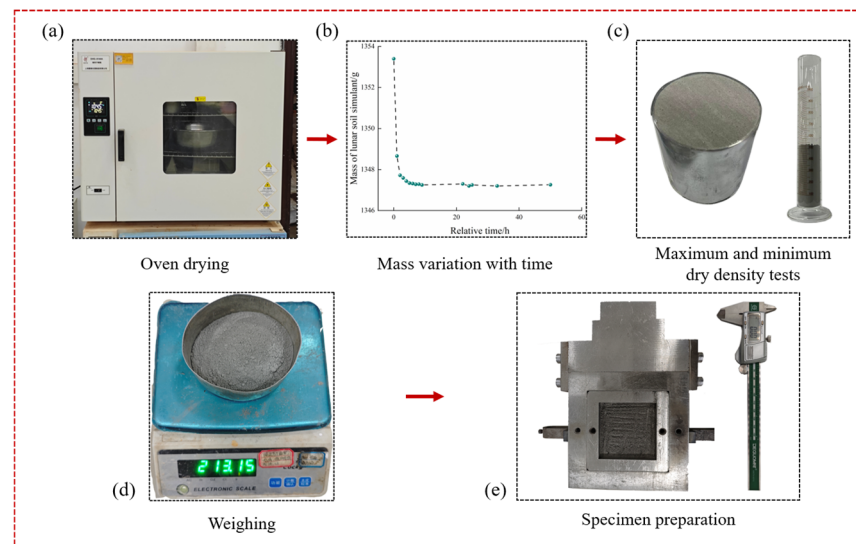


Figure 2. The specimen preparation procedure of lunar regolith simulant. (a) Oven-dried lunar regolith simulant; (b) variation in the mass of the lunar regolith simulant with drying time; (c) determination of the maximum and minimum dry densities of the lunar regolith simulant using vibratory compaction and funnel deposition, respectively; (d) weighing of the lunar regolith simulant; (e) layer-by-layer preparation of a cubic lunar regolith simulant specimen with a side length of 70 mm.

The two layer interfaces were located approximately 23.3 mm and 46.7 mm above the specimen base. The nominal shear plane, defined by the horizontal split between the upper and lower shear boxes, was located 35 mm above the base. Each specimen remained in the shear box and was tested without removal or repositioning. The low funnel outlet height and uniformly moving feeding position were used to reduce particle segregation during deposition. Nevertheless, because the simulant has a particle-size range of 0–2 mm, local particle-size segregation cannot be completely excluded. The standardized preparation procedure was therefore intended to improve specimen-to-specimen consistency rather than to ensure complete homogeneity.

Direct shear tests were conducted on lunar regolith simulant specimens with relative density levels of 75%, 90%, and 100% under different temperatures and normal stress conditions. Detailed test parameters are listed in Table 1. Four target temperature levels of 25 °C, 60 °C, 120 °C, and 180 °C were considered, along with normal stresses of 50 kPa, 100 kPa, and 150 kPa.

Table 1. Test scheme for direct shear tests on lunar regolith simulant.

Relative Density	Temperature/°C	Normal Stress/kPa
75%, 90%, 100%	25	50, 100, 150
	60	50, 100, 150
	120	50, 100, 150
	180	50, 100, 150

2.3. Test Apparatus and Procedure

Direct shear tests were conducted using a multi-field coupled shear testing device (Figure 3a). The direct shear apparatus was jointly developed by Guizhou University (Guiyang, China) and Changchun Kexin Test Instrument Co., Ltd. (Changchun, China). The apparatus comprised normal and shear loading systems, a temperature-control system, a data-acquisition system, and a shear box. The maximum load capacities of the normal and shear loading systems were both 200 kN. The displacement resolution was 1 µm, and the load and displacement signals were acquired at a sampling frequency of 64 Hz. The

controllable temperature range extended from ambient laboratory conditions to 300 °C. A built-in PT100 resistance temperature detector was used to monitor the chamber temperature. Further details of the apparatus are provided in the reference [46]. The apparatus was equipped with a conventional split shear box with internal dimensions of 70 × 70 × 70 mm. Shearing was induced by the relative horizontal displacement of the upper and lower box halves. The nominal shear plane coincided with the horizontal split at the mid-height of the specimen, 35 mm above the specimen base (Figure 3b). The test chamber was enclosed to limit heat loss and temperature fluctuations but was not evacuated; therefore, all tests were conducted under terrestrial atmospheric pressure. A circulating-water cooling system was operated during heating to protect the apparatus. Chamber temperature was monitored using the built-in PT100 sensor, whereas specimen temperature was monitored using thermocouples attached to the specimen surface. The test procedure was as follows:

- (1) Before loading, thermocouples were attached to the specimen surface.
- (2) The normal load was applied at a rate of 0.05 kN/s and maintained at the target value throughout the heating and shearing stages. The self-weight of the upper loading platen was included in the calculation of normal stress.
- (3) The circulating-water cooling system and temperature-control system were activated, and the specimen was heated to the target temperature. After the chamber reached the prescribed temperature, this temperature was maintained for 4 h to promote thermal equilibration within the specimen.
- (4) The specimen was sheared under displacement control at a constant horizontal displacement rate of 0.04 mm/min. The prescribed normal load and temperature were maintained throughout shearing.
- (5) After shearing, the normal load was released, and the upper and lower box halves were carefully opened and disassembled to expose the post-shear surface. The exposed surface was subsequently photographed and scanned using an EET3DS binocular three-dimensional laser scanning system (Beijing Xunheng Technology Co., Ltd., Beijing, China) as shown in Figure 3c.

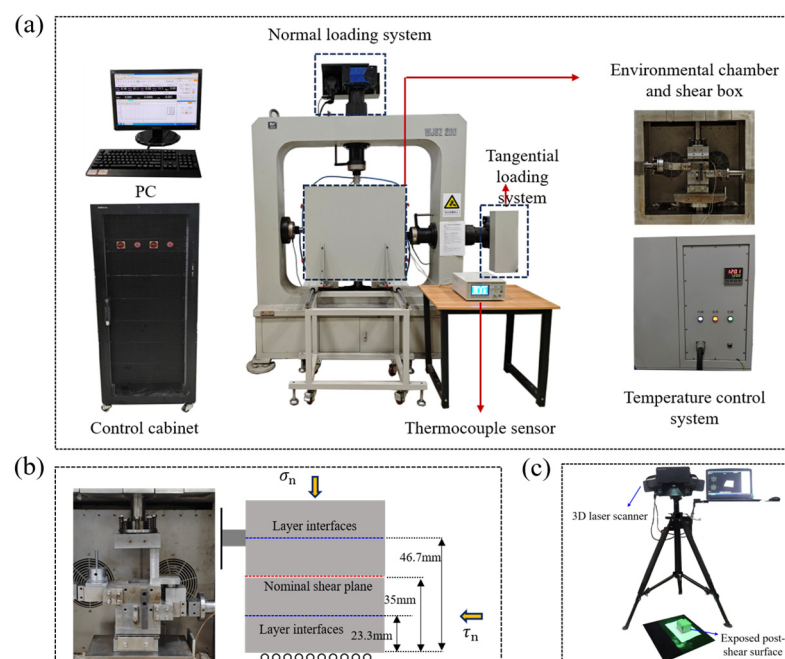


Figure 3. Experimental apparatus. (a) Multi-field coupled shear testing device; (b) schematic illustration of the layer interfaces and nominal shear plane; (c) 3D laser scanner.

All 36 tests were conducted using the same specimen-preparation, loading, heating, thermal-equilibration, shearing, and data-acquisition procedures. To assess experimental repeatability, three independently prepared specimens were tested at $D_r = 75\%$, $\sigma_n = 150$ kPa, and $T = 25$ °C. As shown in Supplementary Figure S1 and Table S1, the repeated tests exhibited similar shear stress–displacement responses and consistent peak and residual shear strengths. The peak shear strength was identified as the first local maximum preceding the post-peak stress drop. Consistent with the definition in Section 3.1, the residual shear strength was taken as the post-peak minimum preceding the subsequent renewed hardening. The mean peak and residual shear strengths were 102.94 and 81.65 kPa, with corresponding coefficients of variation (CVs) of 2.92% and 3.47%, respectively. The limited variability supports the repeatability of the experimental procedure under the selected condition. Because repeat tests were not conducted across the full test matrix, this assessment is restricted to the selected condition.

3. Results and Analysis

3.1. Shear Stress–Displacement Curve

Figure 4 shows the shear stress–displacement curves of lunar regolith simulant specimens with different relative densities (D_r levels under varying temperatures and normal stress conditions. The shear stress–displacement curve of the lunar regolith simulant can be divided into the following four stages: (1) Elastic deformation stage: shear stress increases linearly with increasing shear displacement. (2) Plastic deformation stage: the increase rate of shear stress with shear displacement nonlinearly decreased. (3) Strain softening stage: after reaching the peak shear strength, the shear stress drops rapidly, forming a pronounced hump in the curve. (4) Residual strength stage: Post-peak shear stress evolution varies significantly for the lunar regolith simulant specimens of different relative densities (D_r) levels. For specimens with $D_r = 75\%$, the post-peak shear stress decreases rapidly and subsequently increases with further shear displacement. In contrast, for specimens with $D_r = 90\%$ and 100% , the post-peak shear stress generally decreases and then tends to stabilize, with local fluctuations under some conditions. The post-peak increase at $D_r = 75\%$ may be associated with particle accumulation and compaction within the shear zone, together with the additional resistance generated by a non-planar shear surface. This response is discussed further in Section 4.1. In this study, the residual shear strength was operationally defined according to the post-peak response. For specimens with $D_r = 75\%$, the post-peak minimum shear resistance was taken as the residual shear strength, representing the lowest resistance attained after peak failure and before subsequent renewed hardening. For specimens with $D_r = 90\%$ and 100% , the residual shear strength was taken as the stabilized large-displacement shear resistance near the end of the test.

For all lunar regolith simulant specimens, both the peak and residual shear strengths generally increase with increasing normal stress. This trend is consistent with the greater frictional resistance mobilized at particle contacts under increased normal confinement. Averaged across the four temperature levels, increasing the normal stress from 50 to 150 kPa increases the peak shear strength by 40%, 147%, and 108% for specimens with $D_r = 75\%$, 90%, and 100%, respectively, while the corresponding increases in residual shear strength are 92%, 148%, and 223%. These results indicate that the effect of normal stress on shear strength depends on relative density and differs between the peak and residual responses. The percentage increase in peak shear strength is greatest at $D_r = 90\%$ and does not vary monotonically with relative density, whereas that in residual shear strength increases progressively with relative density. The non-monotonic peak response may reflect the competing influences of particle interlocking and the progressively reduced scope for particle rearrangement at high relative density, whereas the residual response is more

closely associated with frictional sliding under normal confinement within the developed shear zone.

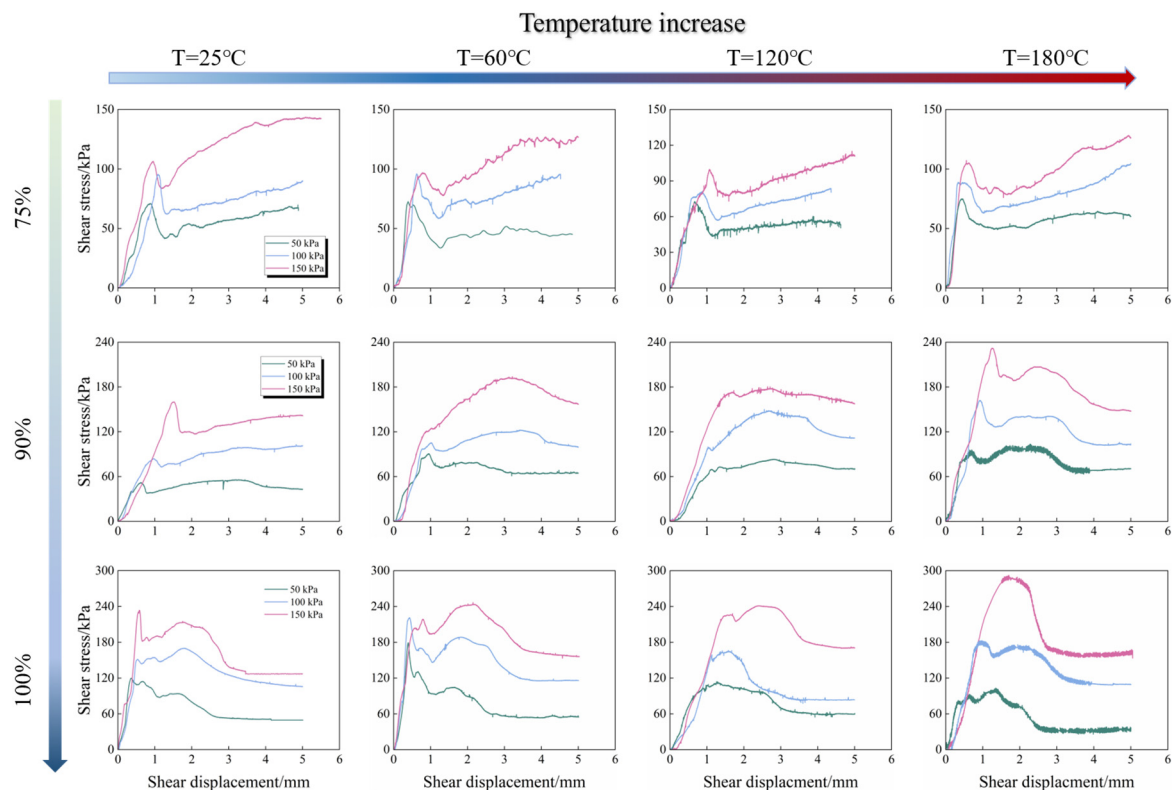


Figure 4. The shear stress–displacement curve of lunar regolith simulant specimens.

3.2. Effects of Relative Density and Temperature on Shear Strength

Each plotted value in Figures 5 and 6 represents an individual test result rather than a replicate mean. Because replicate tests were not performed for every condition, condition-specific error bars are not available for the complete test matrix. Figure 5 shows the evolution of the peak shear strength and residual strength of the lunar regolith simulant specimens with relative density at each temperature level. The effect of relative density on the peak shear strength is pronounced, whereas its influence on residual shear strength is comparatively limited. At the same normal stress level, the peak shear strength generally increased with increasing relative density. For example, under a normal stress of 150 kPa at 25 °C, the peak shear strengths of lunar regolith simulants with 75%, 90%, and 100% compaction are 106, 159, and 233 kPa, respectively. These results indicate that the shear resistance before peak failure is strongly affected by the initial particle-packing state. With increasing relative density, the particle contact network becomes denser and geometric interlocking becomes more pronounced, resulting in a higher mobilized peak shear strength. The post-peak response, however, varies with relative density. As defined in Section 3.1, for specimens with $D_r = 75\%$, the residual shear strength corresponds to the post-peak minimum preceding the subsequent renewed hardening, whereas for specimens with $D_r = 90\%$ and 100% , it corresponds to the stabilized large-displacement shear resistance. Despite these different post-peak response modes, the residual shear strength shows a smaller overall variation with relative density than the peak shear strength. This contrast indicates that the initial particle-packing state has a stronger influence on the mobilized peak resistance than on the adopted post-peak reference resistance. This general behavior is consistent with that commonly observed in terrestrial sands.

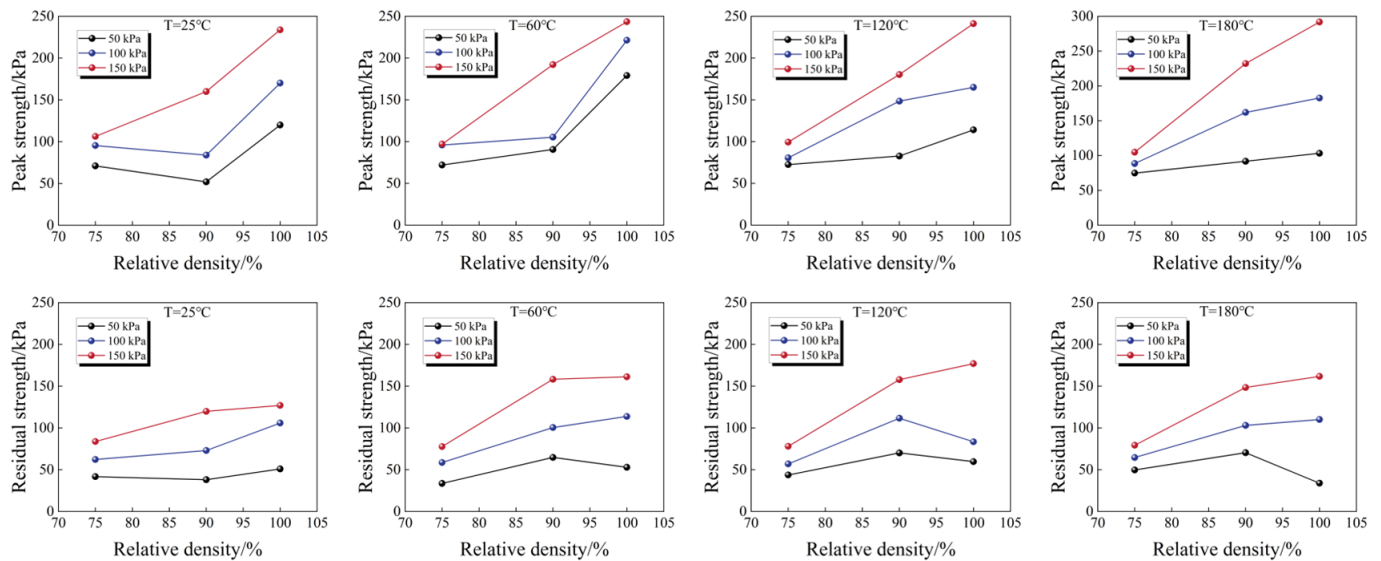


Figure 5. Variations in peak and residual shear strengths with relative densities under different temperatures and normal stresses. Symbols represent individual test results rather than replicate means.

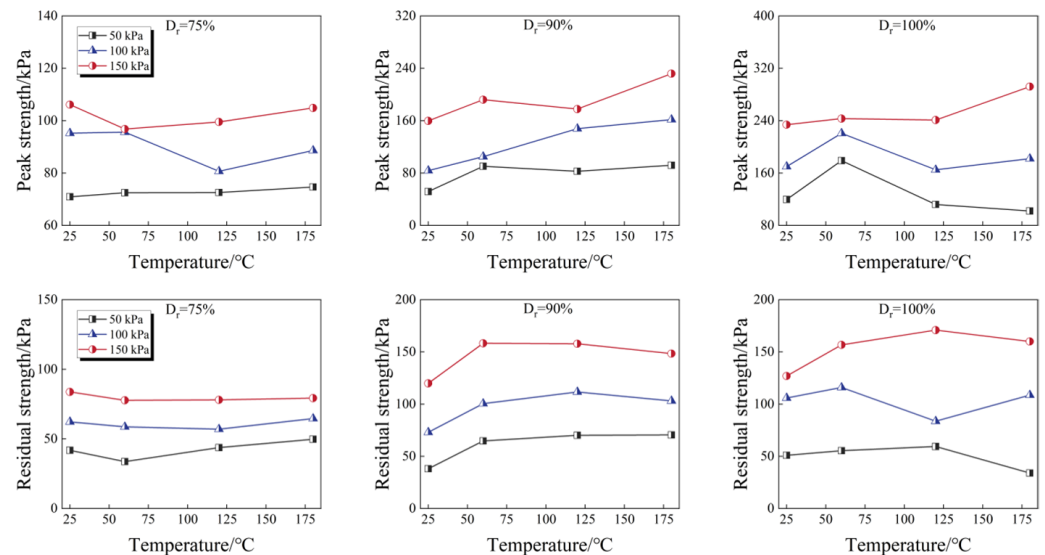


Figure 6. Variations in peak and residual shear strengths with temperature under different relative densities and normal stresses. Symbols represent individual test results rather than replicate means.

Figure 6 shows the evolution of the peak shear strength and residual strength of the lunar regolith simulant specimens with temperature for different relative density specimens. For specimens with 75% relative density, the peak shear strength shows minimal variation with increasing temperature. In contrast, specimens with 90% relative density exhibit a marked increase in peak strength with increasing temperature. For specimens with 100% compaction, a slight increase in peak strength is observed under a normal stress of 150 kPa, while under 50 kPa and 100 kPa, it generally decreases with increasing temperature. Compared with peak shear strength, residual shear strength shows smaller and less systematic variations with temperature. The above results indicate that the influence of temperature on shear strength is closely related to both relative density and normal stress. Relative density determines the initial particle-packing structure and degree of particle interlocking, whereas normal stress affects the contact forces and confinement between particles during shearing. Therefore, temperature-induced changes in particle contact conditions may produce different shear responses under different packing and

stress states. The temperature effect on the shear strength of the lunar regolith simulant is thus considered to be a state-dependent response jointly controlled by relative density and normal stress.

3.3. Analysis of Shear Failure Morphology

Three-dimensional laser scanning was used to reconstruct the exposed post-shear surfaces. The point-cloud data were processed by outlier removal, Kriging interpolation, detrending, and horizontal correction, as shown in Figure 7. The surface morphology was quantified using the peak-to-valley elevation difference, Δh , and the root-mean-square slope, Z_2 , which characterize surface relief and overall roughness, respectively. The peak-to-valley elevation difference was calculated as

$$\Delta h = h_{\max} - h_{\min} \quad (2)$$

where $h_{\max}$ and $h_{\min}$ are the maximum and minimum elevations within the processed surface. To determine Z_2 , parallel profiles were extracted at intervals of 0.1 mm along two orthogonal directions. For the i -th profile,

$$Z_{2,i} = \sqrt{\frac{1}{L_i} \int_0^{L_i} \left(\frac{dz}{dx} \right)^2 dx} \quad (3)$$

where L_i is the length of a profile line, $\frac{dz}{dx}$ is the first derivative of Z (profile elevation) along x direction. The Z_2 values of all profiles were averaged to characterize the overall roughness of the scanned surface:

$$Z_2 = \frac{1}{M} \sum_{i=1}^N Z_{2,i} \quad (4)$$

where M is the total number of profiles. A larger Z_2 indicates greater local slope variation and a rougher surface, whereas a smaller Z_2 indicates a smoother surface [47].

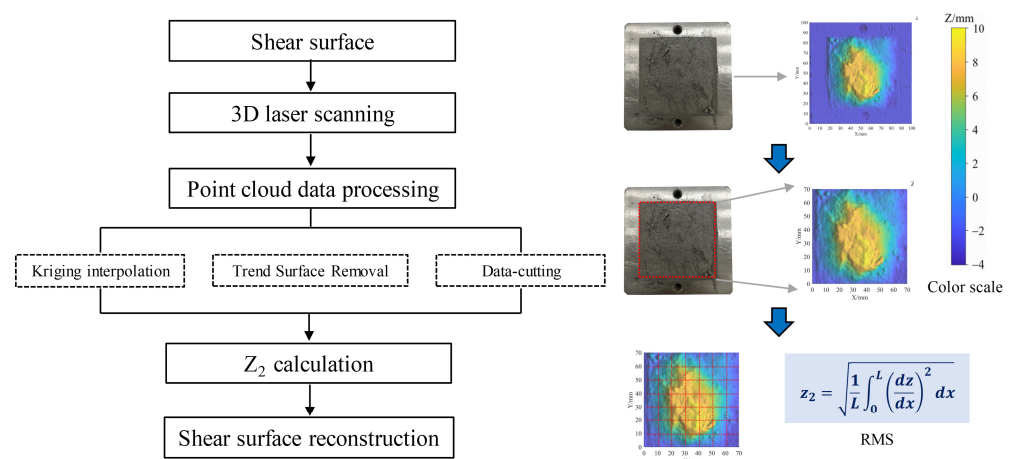


Figure 7. Flowchart of morphology analysis of the exposed post-shear surface of lunar regolith simulant.

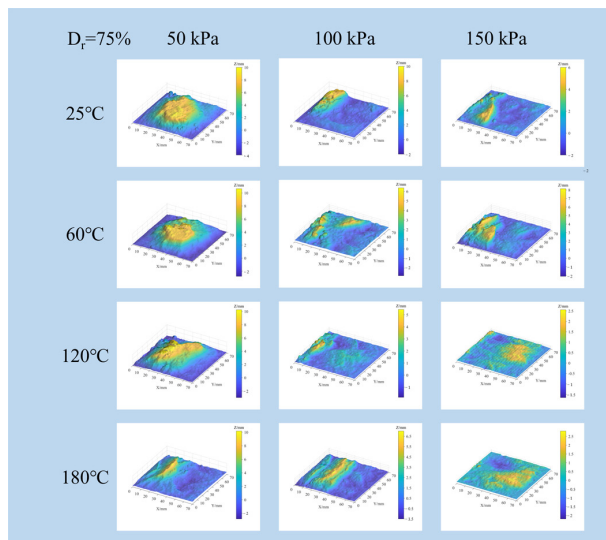
Table 2 presents the peak-to-valley elevation differences in the exposed post-shear surfaces. The value of Δh generally decreased with increasing normal stress, and this reduction was more pronounced at $D_r = 75\%$. An overall decrease in Δh was also observed with increasing relative density, although local deviations occurred under some temperature and normal-stress conditions. These results indicate that denser particle packing and stronger normal confinement were generally associated with less pronounced post-shear

surface relief. For specimens with $D_r = 75\%$, temperature had a limited influence on Δh under a normal stress of 50 kPa, whereas an overall decreasing tendency was observed with increasing temperature under normal stresses of 100 and 150 kPa. For specimens with $D_r = 90\%$ and 100% , Δh generally decreased with increasing temperature, although local non-monotonic variations occurred under some conditions. These results indicate that the temperature-dependent evolution of post-shear surface relief varies with the initial particle-packing state and normal confinement.

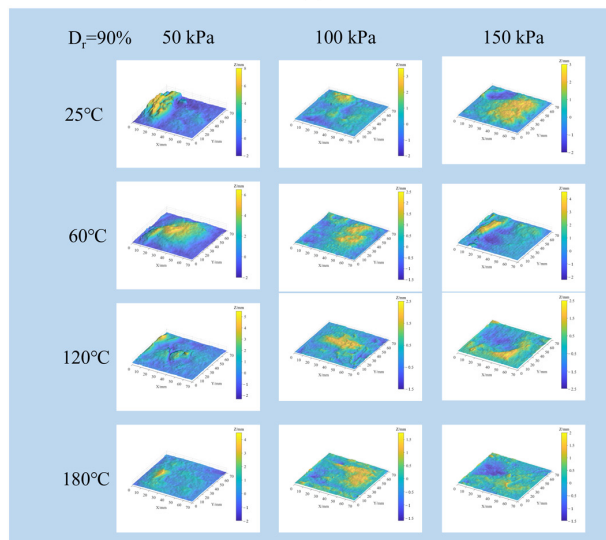
Table 2. Peak-to-valley elevation difference in the exposed post-shear surface for lunar regolith simulants with different relative densities (D_r) levels.

Relative Density	Temperature	50 kPa	100 kPa	150 kPa
		Peak-to-Valley Elevation Difference in the Exposed Post-Shear Surface		
$D_r = 75\%$	25 °C	14 mm	12 mm	8 mm
	60 °C	13 mm	9 mm	10.2 mm
	120 °C	13 mm	7.2 mm	4.2 mm
	180 °C	13 mm	8.5 mm	5 mm
$D_r = 90\%$	25 °C	10 mm	5.4 mm	5 mm
	60 °C	8.4 mm	4 mm	6.6 mm
	120 °C	7.6 mm	4 mm	5 mm
	180 °C	6.5 mm	3.4 mm	3.5 mm
$D_r = 100\%$	25 °C	8 mm	7.2 mm	7 mm
	60 °C	6.2 mm	6.5 mm	3.8 mm
	120 °C	5.3 mm	4.4 mm	5.4 mm
	180 °C	4.5 mm	4 mm	4.3 mm

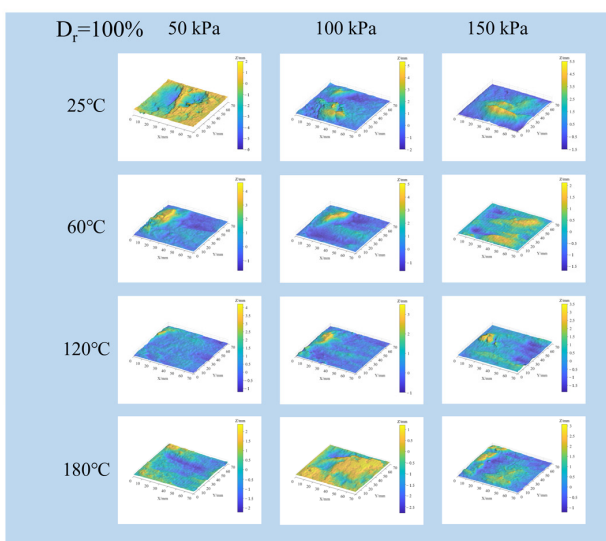
Figure 8d–f show the evolution of the Z_2 value for the exposed post-shear surface morphology with varying relative density under different temperature and normal stress conditions. For the 75% relative density, the Z_2 value of the exposed post-shear surface generally decreases with increasing normal stress and temperature. For the 90% and 100% relative density, the Z_2 value of the exposed post-shear surface generally decreases with increasing temperature. However, for the 100% relative density specimen under a normal stress of 150 kPa, Z_2 initially decreases then increases with increasing temperature, and the evolution of the Z_2 value with normal stress exhibits significant difference under different temperatures. At $D_r = 75\%$, the relatively loose particle arrangement provides greater scope for particle rearrangement and local surface fluctuation during shearing. Increasing normal stress enhances confinement and restricts particle movement, leading to an overall reduction in surface roughness. As relative density increases, the initial particle packing becomes denser and the scope for further rearrangement and local contraction decreases; consequently, the additional influence of normal stress on Z_2 becomes less pronounced. Meanwhile, stronger particle interlocking in denser specimens may promote local particle overriding and the development of surface steps. The measured Z_2 therefore reflects the combined effects of normal confinement, particle rearrangement, and density-dependent interlocking, which may account for the non-monotonic variations observed under some conditions.



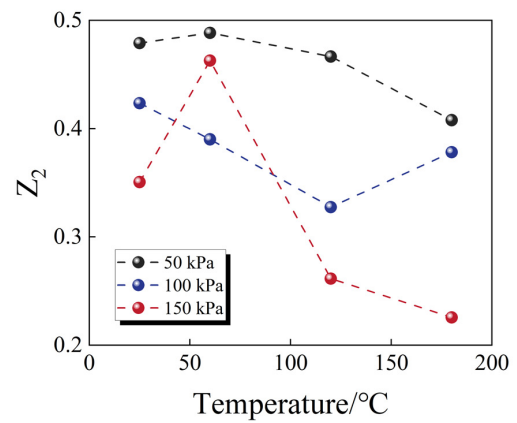
(a)



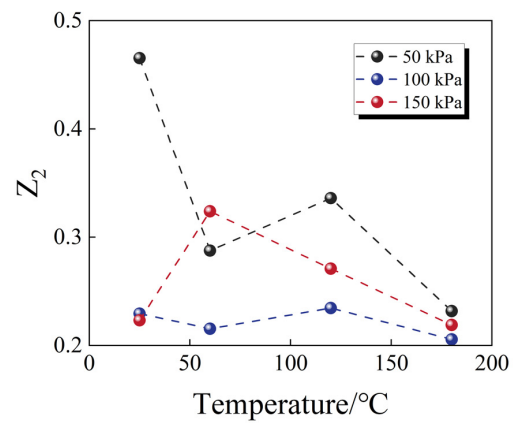
(b)



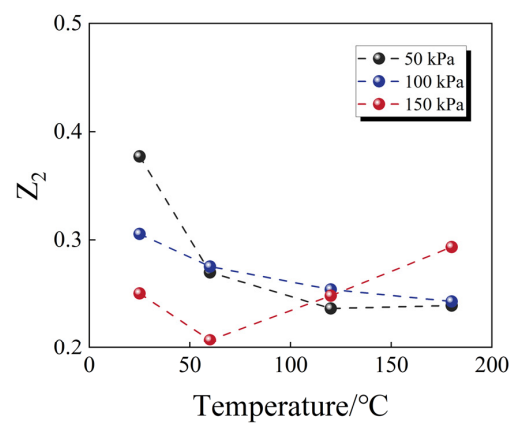
(c)



(d)



(e)



(f)

Figure 8. Three-dimensional reconstruction and roughness of the exposed post-shear surfaces. (a–c) Reconstructed surfaces for $D_r = 75\%$, 90% , and 100% , respectively; (d–f) corresponding variations in Z_2 with temperature and normal stress.

4. Discussion

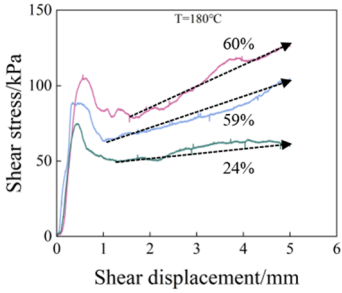
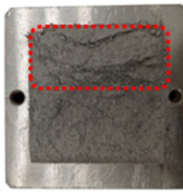
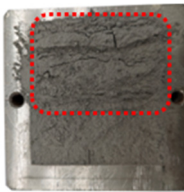
4.1. Relationship Between Shear Behavior and Shear Surface Morphology

Table 3 compares the shear stress–displacement curves and high-resolution images of the exposed post-shear surface for lunar regolith simulant specimens with a low compaction of 75%. After reaching the peak shear strength, the shear stress of the specimens rapidly decreases to a post-peak minimum and subsequently increases significantly with further shear displacement. Shear surface images show the formation of loose particle accumulation along the shear direction, hindering further shear motion. Particle accumulation refers to the progressive buildup of displaced and loosened particles during the relative movement of the upper and lower shear-box halves. These accumulated particles may obstruct further relative movement and contribute to the increase in post-peak shear resistance. This feature was identified qualitatively from the post-shear images rather than quantified independently. Compared with the response at 50 kPa, the post-peak increase in shear stress was generally greater under normal stresses of 100 and 150 kPa, although no consistently monotonic difference was observed between these two stress levels. Stronger normal confinement increases the resistance mobilized during particle accumulation and continued relative displacement. However, the post-peak increase cannot be attributed solely to particle accumulation. During direct shearing, the actual shear surface may become inclined and non-planar; particle climbing, geometric interlocking, and the associated direct-shear boundary constraints may therefore also contribute to the measured post-peak resistance.

Table 3. Comparison of shear behavior and shear surface morphology of lunar regolith simulants with 75% compaction.

Shear Stress–Displacement Curves	50 kPa	100 kPa	150 kPa
$T=25^{\circ}\text{C}$ 70% 43% 61% 50 kPa 100 kPa 150 kPa	Shear direction $Z_2 = 0.4789$	$Z_2 = 0.4235$	$Z_2 = 0.3506$
$T=60^{\circ}\text{C}$ 59% 62% 35%	$Z_2 = 0.4885$	$Z_2 = 0.3902$	$Z_2 = 0.4628$
$T=120^{\circ}\text{C}$ 42% 46% 27%	$Z_2 = 0.4665$	$Z_2 = 0.3276$	$Z_2 = 0.2615$

Table 3. Cont.

Shear Stress–Displacement Curves	50 kPa	100 kPa	150 kPa
	 $Z_2 = 0.4078$	 $Z_2 = 0.3782$	 $Z_2 = 0.2257$

On the other hand, the Z_2 value generally decreased with increasing normal stress, indicating an overall reduction in post-shear surface roughness under stronger normal confinement. Increased confinement restricts large particle movements and local surface fluctuations, resulting in a smoother final surface. Thus, normal stress may simultaneously increase the resistance to continued shearing while suppressing the final surface roughness. The post-peak stress response and Z_2 therefore characterize different aspects of the shearing process.

Figure 9 shows high-resolution images of the exposed post-shear surface for lunar regolith simulant specimens with high compaction (90% and 100%). The high-compaction lunar regolith simulant specimens did not exhibit significant particle accumulation during the shearing process. The post-peak shear stress–displacement curve of the high-compaction specimens differs notably from that of the low-compaction specimens, showing a decrease followed by stabilization as shear displacement increases, with local fluctuations observed (such as the stress–displacement curves at 25 °C and 60 °C for the 100% compaction specimens in Figure 4). For specimens with ($D_r = 90\%$) and (100%), distinct step-like features were observed on the post-shear surfaces, as indicated by the yellow outlines in Figure 9. At higher relative density, particle rearrangement becomes more constrained, while geometric interlocking among the irregular particles can be more fully mobilized during shearing. Local particle overriding and rearrangement may therefore promote the development of an irregular, non-planar shear surface, contributing to the observed step-like relief. The two preparation interfaces at approximately 23.3 and 46.7 mm did not coincide with the nominal shear plane at 35 mm, reducing the likelihood of direct sliding along an artificial layer interface. Nevertheless, shear deformation in a split-box direct shear test is distributed over a finite zone adjacent to the nominal shear plane. The possible effects of local particle-size segregation and fabric heterogeneity associated with layered preparation on the observed surface morphology therefore cannot be completely excluded. During continued shearing, successive particle overriding and rearrangement alter the degree of geometric interlocking and may contribute to local fluctuations in the post-peak shear response.

4.2. Phenomenological Parameterization of the Shear Stress–Displacement Response

The macroscopic shear response of the lunar regolith simulant is governed by the evolution of its load-bearing interparticle contact network. During shearing, particle rearrangement, sliding, rotation, and the progressive loss of interlocking continuously alter this network, eventually leading to the development of a localized shear zone. Figure 10 schematically relates the characteristic stages of the shear stress–displacement response to the evolution of the phenomenological damage variable D . During the elastic deformation stage, the load-bearing contact network remains largely intact and D is close to 0. During the plastic deformation stage, irreversible particle rearrangement and contact-network

degradation reduce the rate of shear-stress increase, while D progressively increases. During strain softening, continued degradation of the contact network is accompanied by a marked decrease in shear stress. When the specimen reaches the residual strength stage, the shear response approaches a residual level and D tends toward 1. In the present study, D is defined as a phenomenological variable that characterizes the progressive degradation of the load-bearing contact network, rather than a directly measured microstructural quantity.

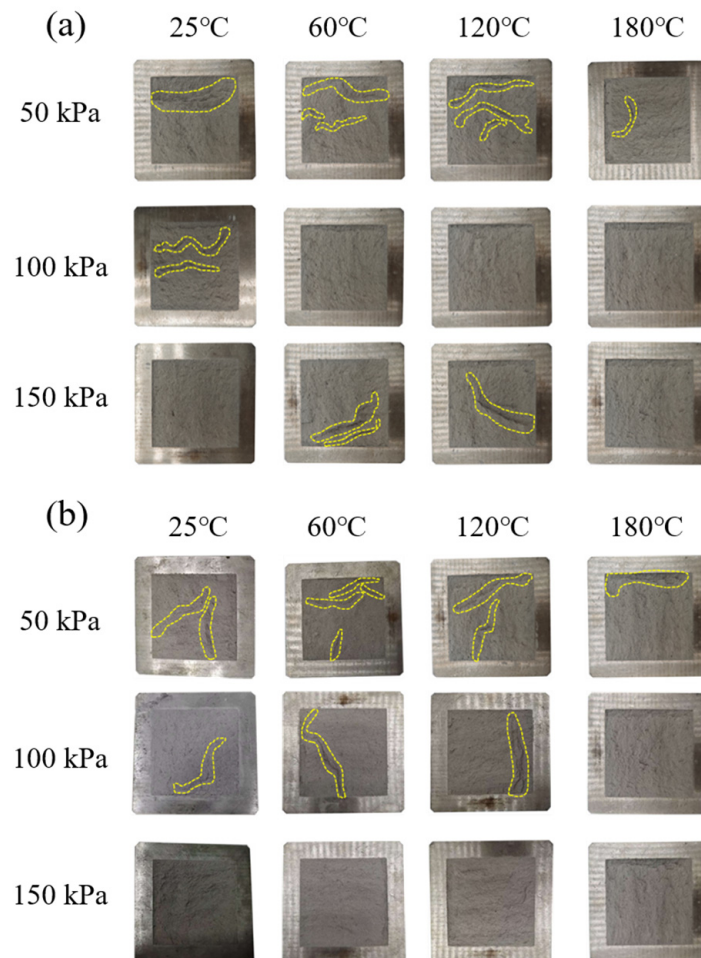


Figure 9. High-resolution shear surface images of lunar regolith simulant specimens under different temperature and normal stress conditions. (a) Specimens with $D_r = 90\%$; (b) specimens with $D_r = 100\%$.

Zou et al. [48] introduced a log-logistic function to characterize the evolution of the damage variable during soil shearing:

$$D = \frac{1}{1 + au^{-r}} \quad (5)$$

where u is the shear displacement, a and r are fitting parameters governing the position and rate of the transition in D , respectively. For positive values of a and r , D increases monotonically from approximately 0 to 1 with increasing shear displacement. By incorporating Equation (5), the measured shear stress–displacement response can be expressed as,

$$\tau = K_s u \left(1 - \frac{1}{1 + au^{-r}} \right) + \frac{\tau_r}{1 + au^{-r}} = \frac{\tau_r}{u_1} u \left(1 - \frac{1}{1 + au^{-r}} \right) + \frac{\tau_r}{1 + au^{-r}} \quad (6)$$

where a and r are parameters of damage evolution model, which can be obtained by fitting the damage evolution process; K_s is the shear stiffness; u is shear displacement; and

τ_r is the residual strength. As shown in Figure 11, The formulation provided generally good fits to the 36 measured shear stress–displacement curves, with a mean coefficient of determination (R^2) of 0.949. For the case with the lowest R^2 value of 0.873, the measured response exhibited pronounced local fluctuations and a more complex post-peak evolution that were not fully captured by the smooth phenomenological formulation. The parameters k_s , a , and r were fitted independently to each measured curve. Accordingly, the formulation is used here to parameterize the measured responses and to compare the fitted parameters across the investigated thermo-mechanical conditions.

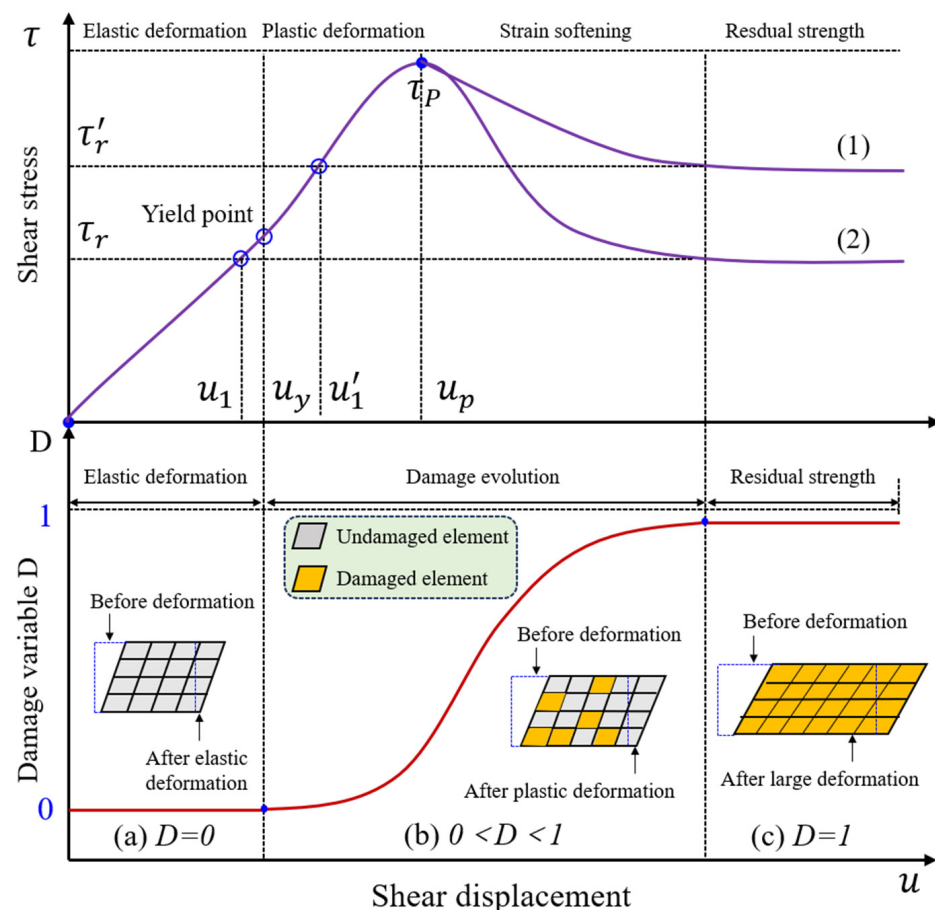


Figure 10. Schematic relationship between the shear stress–displacement response and the evolution of the phenomenological damage variable D . Adapted from Zou et al. (2024) [48], *Landslides*, Springer Nature. Reproduced with permission from Springer Nature.

The fitted formulation was subsequently used to evaluate the shear-stiffness parameter and the evolution of the phenomenological damage variable. Figure 12 shows the variation with relative density, normal stress, and temperature. Under the same compaction and temperature conditions, the shear stiffness is greater at higher normal stress. Meanwhile, shear stiffness generally increases with the increasing compaction. For lunar regolith simulant specimen with 75% and 90% compaction, the shear stiffness generally increases with increasing temperature, although a local decrease is observed. However, For the 100% compaction, the shear stiffness first decreases and then increases with increasing temperature.

The evolution of the phenomenological damage variable was obtained from the fitted formulation. Figure 13 compares the values of corresponding to peak shear strength under different relative densities and normal stresses at 25 °C. The damage variable at peak shear strength is greater under conditions of higher compaction and normal stress.

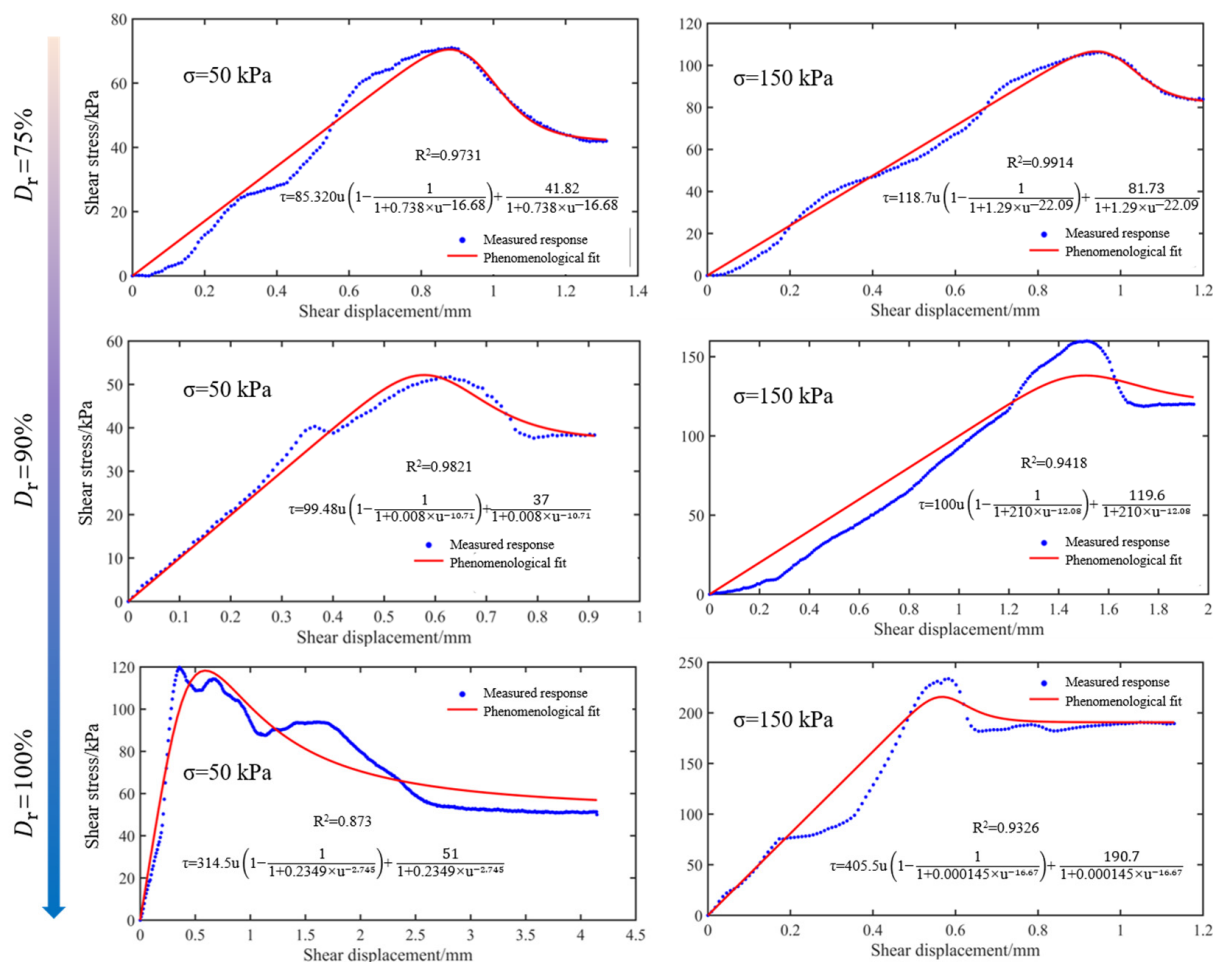


Figure 11. Comparison of the measured shear stress–displacement responses with the corresponding phenomenological fits.

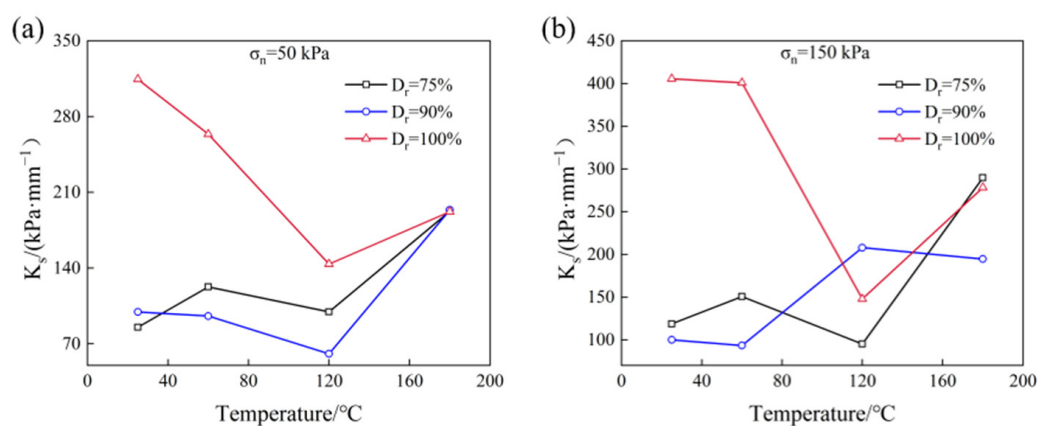


Figure 12. Evolution of shear stiffness in lunar regolith simulant specimens under varying relative density and temperature conditions: (a) under 50 kPa normal stress; (b) under 150 kPa normal stress.

4.3. Relevance to Lunar Drilling and Sampling

The interaction between lunar regolith and a drilling tool involves particle shearing, rearrangement, and relative movement. The associated mechanical response is jointly influenced by the initial particle-packing state, normal confinement, and temperature. The measured shear strength and post-peak response characterize the resistance and deformation of regolith under continued disturbance. Within the tested range, both peak and residual shear strengths generally increased with normal stress. Increasing relative

density mainly enhanced the peak strength and altered the subsequent softening and stabilization behavior. The temperature effect varied with relative density and normal stress, indicating that the influence of thermal conditions on drilling-related mechanical behavior is closely associated with the particle-packing state and degree of confinement. For specimens with $D_r = 75\%$, the shear stress decreased briefly after the peak and subsequently increased with further displacement, accompanied by localized accumulation of loose particles on the exposed post-shear surface. Under continued disturbance, particle accumulation, local compaction, and movement along an undulating shear surface may increase the subsequent shear resistance of loose regolith. This behavior provides insight into the accumulation and migration of disturbed particles during drilling. The present results were obtained from quasi-static direct shear tests under constant normal stress and primarily characterize the effects of temperature, relative density, and normal confinement on the shear response of the simulant. Actual drilling additionally involves tool rotation, cyclic disturbance, particle transport, and complex stress paths. The results provide baseline data for examining the evolution of shear resistance and deformation in regolith subjected to drilling disturbance and for designing subsequent drilling tool–regolith interaction tests.

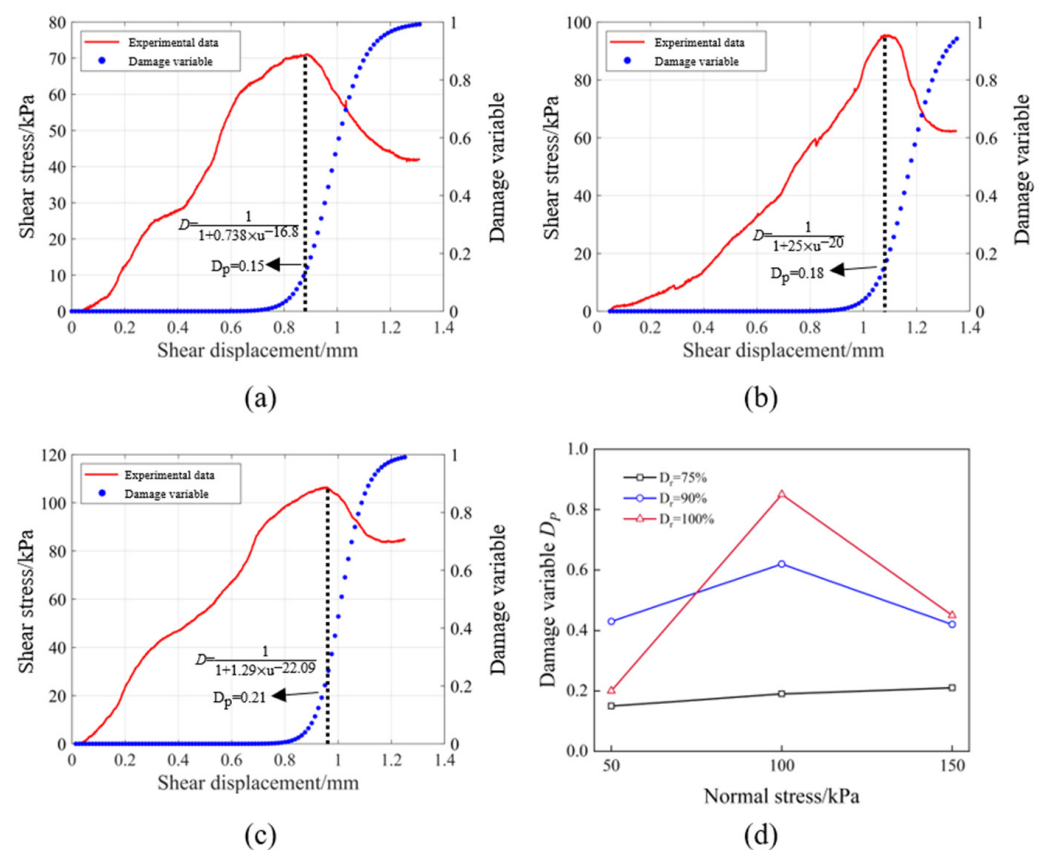


Figure 13. Evolution of the phenomenological damage variable under different relative densities and normal stresses at 25 °C. (a–c) Shear stress–displacement responses and corresponding damage-variable evolution for $D_r = 75\%$ under normal stresses of 50, 100, and 150 kPa, respectively; (d) damage variable corresponding to the peak shear strength at different relative densities and normal stresses.

5. Limitations and Future Work

This study examined the shear response of a lunar regolith simulant under controlled relative densities, normal stresses, and temperature levels. Actual lunar regolith is spatially and vertically heterogeneous, with variations in density, particle-size distribution, mineralogy, maturity, particle fabric, and thermal history. The present results therefore describe comparative trends for the selected simulant under controlled conditions. Application to a

specific lunar region requires calibration against the local material properties and thermal environment. The split-box direct shear test defines a nominal shear location and is subject to nonuniform stress distribution and rigid boundary effects. A standardized three-layer preparation procedure was adopted to improve comparability among specimens, although local segregation or layer-induced fabric differences cannot be completely excluded. Repeatability was assessed using three independently prepared specimens under one selected test condition, which showed limited specimen-to-specimen variability. Additional repeat tests across other conditions are required to quantify variability over the full experimental matrix. All tests were conducted under terrestrial atmospheric pressure rather than lunar vacuum conditions. Although the simulant was oven-dried at 105 °C for 24 h, residual adsorbed water, gases, or surface films may have remained on the particle surfaces. Previous studies have shown that surface cleanliness and adsorbed species can substantially affect interparticle surface forces under different environmental conditions [34,49]. Relative to an airless or fully outgassed vacuum environment, residual adsorbates under terrestrial conditions may reduce surface cleanliness and weaken surface-force contributions to interparticle resistance. Heating may promote desorption and partially reduce this difference. However, because no paired atmosphere–vacuum tests or particle-scale surface characterization were performed, the net influence on the measured macroscopic shear strength cannot be quantified from the present data. The observed temperature-dependent behavior should therefore be interpreted as comparative trends under controlled terrestrial conditions.

Beyond these experimental limitations, the present phenomenological formulation is descriptive rather than predictive. Its parameters were determined separately for each measured response and were not expressed as functions of relative density, normal stress, or temperature. Therefore, before the formulation can be used to predict shear responses under untested thermo-mechanical conditions, quantitative relationships between the formulation parameters and these controlling variables must be established and independently validated.

Future work should include paired atmospheric–vacuum shear tests, thermal cycling, particle-scale friction measurements, and surface physicochemical characterization. Rotational, cyclic, and combined loading tests are also needed to represent drilling-induced disturbance more realistically. The effects of particle gradation, mineralogical composition, and reduced gravity should be considered to improve the relevance of the results to lunar drilling conditions.

6. Conclusions

This study investigated the effects of temperature, relative density, and normal stress on the shear behavior of lunar regolith simulants through direct shear tests under coupled thermal–mechanical conditions. The relationship between the post-shear surface morphology and the measured shear response was also examined. The main conclusions are as follows:

- (1) Within the tested range, the peak and residual shear strengths generally increased with normal stress. Peak shear strength also generally increased with relative density, whereas residual shear strength was less sensitive to the initial relative density.
- (2) The effect of temperature on peak shear strength was not consistently monotonic and varied with both relative density and normal stress, indicating a state-dependent response. Residual shear strength was generally less sensitive to temperature than peak shear strength.
- (3) The post-peak response varied with relative density. Specimens with $D_r = 75\%$ tended to exhibit a post-peak increase in shear resistance, whereas specimens with $D_r = 90\%$ and 100% showed more pronounced strain softening followed by stabilization. Three-

dimensional measurements showed that the peak-to-valley elevation difference and roughness parameter Z_2 of the post-shear surface generally decreased with increasing relative density or normal stress.

- (4) The damage-based log-logistic formulation provided a phenomenological parameterization of the 36 measured shear stress–displacement curves, with a mean of R^2 of 0.949. The fitted shear-stiffness and damage-related parameters provide quantitative descriptors for comparing the measured responses across the investigated thermo-mechanical conditions.

Overall, from a broader soil-mechanics perspective, the tested lunar regolith simulant exhibits the fundamental frictional-granular behavior common to terrestrial sands. The effects of relative density and normal confinement, as well as particle rearrangement, sliding, and interlocking during shearing, are therefore not regarded as uniquely lunar. The relevance to lunar regolith lies primarily in the material characteristics and environmental conditions under which these common mechanisms operate. In the present experiments, temperature was the principal lunar-relevant environmental variable directly investigated, and its effect on shear strength was strongly dependent on relative density and normal stress. The angular and irregular morphology of the simulant particles may additionally influence particle interlocking and post-peak resistance relative to many commonly studied sub-rounded quartz sands, although particle angularity itself is not unique to lunar materials. Other important lunar conditions, including vacuum, reduced gravity, surface cleanliness, and regolith maturity, were not reproduced in the present tests and require further investigation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16178527/s1>, Figure S1: The Shear stress–displacement responses of three independently prepared specimens tested at $D_r = 75\%$, $\sigma_n = 150$ kPa, and $T = 25$ °C. Table S1: Repeatability of peak and residual shear strengths under the selected test condition.

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