An Experimental Framework for Evaluating Lunar Regolith Adhesion on Bio-Inspired Ceramic 3D-printed Laminates

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Lunar regolith adhesion presents a major challenge for sustained surface operations, as demonstrated during the Apollo missions, where dust accumulation degraded mechanical systems and hardware performance. The fine, angular morphology and electrostatic charging of regolith promote strong solid-solid interactions with engineering materials, motivating the need for passive, durable mitigation strategies. This work creates an experimental framework to evaluate lotus leaf- and beetle-inspired surface patterns on alumina laminates, fabricated using lithography-based ceramic manufacturing (LCM) for lunar dust mitigation. Previous adhesion testing was completed using the tap-tap and centrifuge test methods. These methods had varying limitations in repeatability and quantification resulting in unreliable results. The new approaches, presented here, use optical profilometry and contact angle goniometry to produce quantitative results, linking surface roughness and wettability with adhesion behavior qualitatively. In this study, we identify and define an experimental approach for quantifying adhesion. With progress in lunar exploration missions, this work offers a systematic framework for evaluating the effectiveness bio-inspired designs for regolith mitigation.

I. Nomenclature

$JSC-1A$	=	Johnson Space Center Bulk Simulant
LCM	=	Lithography-Ceramic Based Manufacturing

II. Introduction

During the Apollo missions, lunar dust presented a major challenge due to its sharp, abrasive, and electrostatically charged morphology. On the lunar surface, regolith readily adhered to equipment, leading to material degradation, increased wear, and impaired functionality [1–8]. Therefore, effective dust mitigation is critical for future long-duration missions, such as those planned under the Artemis program. These mission requirements have driven research into passive strategies that reduce adhesion through surface and material modifications rather than active mechanical removal [9–16].

One promising passive approach involves the use of bio-inspired surface textures[17–19]. With new additive manufacturing methods, micro-scale features modeled after lotus leaves and beetle wings were replicated on ceramic laminates to leverage their superhydrophobic and adhesion-mitigating properties [16]. Such morphology can limit regolith contact area and reduce particle retention. Previous testing using well-known tap-tap and centrifuge methods [16] provided initial adhesion data but suffered from limitations in accuracy and repeatability. This study develops a standardized adhesion testing framework for quantitative results to evaluate bio-inspired ceramic laminates under lunar-relevant conditions. A trade study was performed to assess cleaning protocols, dust deposition methods, environmental control, detachment mechanisms, and quantitative residual measurement techniques. The resulting framework emphasizes repeatability, quantification, and physical relevance to lunar adhesion mechanisms.

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III. Background

A. Lunar Dust Adhesion Mechanisms

Lunar regolith interactions are governed by both adhesion (particle-surface forces) and cohesion (particle-particle forces), which arise from the same underlying surface-force mechanisms. In the lunar environment, the dominant contributors are van der Waals forces and electrostatic charging, with mechanical interlocking further enhancing retention behavior. It has been reported that adhesion-to-weight ratios increase rapidly as particle diameter decreases because adhesive forces scale approximately with particle size while gravitational forces scale with particle volume [20]. As a result, fine and ultrafine particles (<10 µm) dominate adhesion severity. Measurements of simulated lunar dust confirm that the finest fractions exhibit high surface charge density and enhanced interparticle forces, reinforcing their disproportionate role in both adhesion and cohesion [1, 2, 17, 20].

Electrostatic effects are particularly significant under lunar conditions. In the absence of an atmosphere, charge dissipation is limited, allowing particles to accumulate charge through solar ultraviolet photoemission, plasma interactions, and triboelectric processes. Charge distributions have been experimentally quantified in fine and ultrafine simulant particles, demonstrating substantial variability in particle charge magnitude and polarity [1, 2] . Literature further describes how electrostatic charging contributes to dust lofting, transport, and persistent adherence to exposed surfaces [1, 2] .

Mechanical interlocking further strengthens both adhesion and cohesion due to the angular and irregular morphology of lunar regolith grains. Unlike terrestrial sediments subjected to weathering, lunar particles retain sharp edges formed through micrometeoroid impacts [2, 20]. Cohesion is similarly enhanced by geometric interlocking between irregular grains, contributing to the bulk mechanical strength and agglomeration behavior of the regolith.

Capillary forces, which dominate terrestrial dust adhesion through moisture bridging, are negligible in the lunar ultra-high vacuum environment [2]. Accordingly, this study focuses on van der Waals forces, electrostatic charging, and mechanical interlocking as the governing mechanisms influencing regolith retention and removal. These mechanisms directly informed the evaluation criteria used in the subsequent trade study.

B. Bio-Inspired Surface Texture Designs

Micro-textured, bio-inspired surfaces mitigate lunar regolith adhesion by altering particle–surface contact mechanics at the microscale. By reducing the true contact area between particles and the substrate, these engineered textures decrease van der Waals interactions, which scale with effective contact radius. Surface features such as hierarchical roughness and patterned protrusions also disrupt continuous particle-surface contact, limiting mechanical interlocking and reducing stable electrostatic attraction zones. Because adhesion in the lunar environment is governed primarily by dry surface forces rather than capillary effects, modifying surface morphology provides a physics-based method for reducing dust retention without reliance on coatings or active systems.

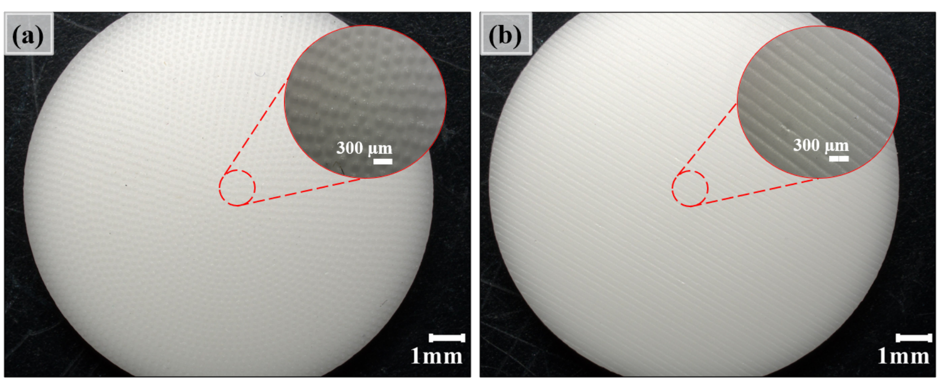

Fig. 1 This image above, taken via microscopy, illustrates our samples (a) the lotus leaf and (b) the beetle wing surface morphology produced on alumina laminates via lithography-based ceramic manufacturing(LCM).

Bio-mimetic designs are particularly advantageous because they replicate naturally evolved strategies for contamination resistance and self-cleaning [17]. Hierarchical surface architectures inspired by the lotus leaf and beetle-wing microprotrusions reduce adhesion by increasing multi-scale surface roughness. [21]. By developing a systematic testing framework for quantifying adhesion and detachment performance, the relationship between engineered surface microstructures and regolith retention can be accurately characterized, enabling the development of reliable and effective passive dust mitigation strategies for lunar exploration.

IV. Experimental Methods

The alumina laminate samples used in this study were manufactured using a CeraFab S65 lithography-based ceramic manufacturing (LCM) system (Lithoz). Three surface configurations were examined: a lotus leaf-inspired texture, a beetle-inspired texture, and an unpatterned control surface. Figure 1 shows microscopy images of the lotus leaf and beetle inspired surfaces achieved using LCM. The LCM samples consisted of 12.7 mm diameter, 1 mm thick alumina disks, with the patterned features fabricated at 10 or 25 μm thicknesses [16]. The patterned samples were manufactured with varying feature thicknesses to investigate the influence of microstructural geometry on adhesion behavior. Sample fabrication was completed prior to this study; the scope of the present work is limited to surface characterization and adhesion testing to establish the framework.

A. Surface Topography Characterization

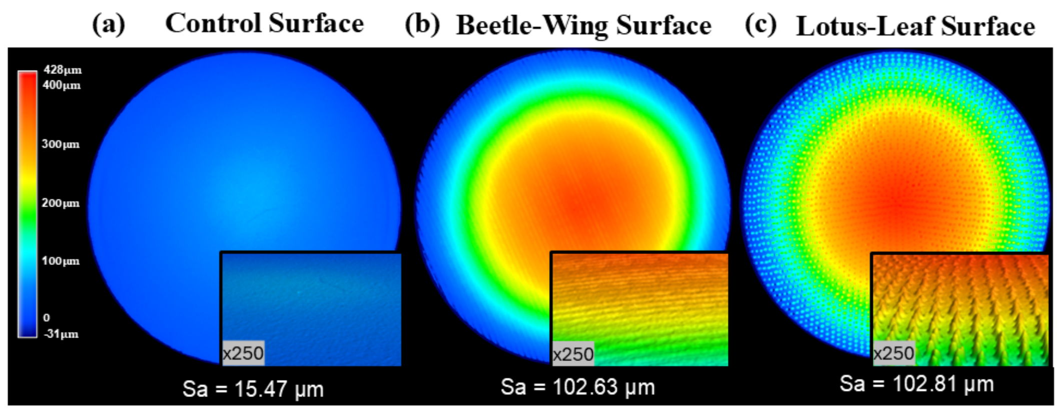

Fig. 2 Height maps with x250 magnified angled-view and corresponding areal roughness values (Sa) shown beneath each image for (a) the control, (b) the beetle-wing-inspired alumina surface, and (c) the lotus-leaf-inspired alumina surface. The images demonstrate clear differences in surface morphology and quantitative roughness metrics. The control surface exhibits a relatively smooth and uniform topology, whereas the lotus leaf and beetle wing biomimetic surfaces display pronounced micro- and nanoscale peaks and valleys. These features correspond to an increased surface roughness.

Surface characterization was performed using a Keyence VR-3000 optical profilometer to provide a quantitative basis for adhesion testing. Areal roughness metrics, arithmetic mean height (Sa), root-mean-square height (Sq), and maximum peak-to-valley height (Sz), were obtained from three-point circular area scans to capture the microtopography influencing particle-surface interactions (Figure 2). Because adhesion strongly depends on real contact area and separation distance, these parameters are critical for interpreting regolith retention.

A 40× objective lens resolved microscale asperities relevant to adhesion. Three-dimensional scans were collected for each specimen under identical magnification and field-of-view conditions to ensure repeatability across the flat control, lotus-leaf, and beetle-wing surfaces. Sa represents average surface deviations, while Sq emphasizes high-amplitude asperities, which can significantly alter effective contact area and adhesion magnitude. Additional parameters, Sz, skewness (Ssk), and kurtosis (Sku), further describe morphology. Peak-dominated surfaces (Ssk > 0) reduce nominal contact area but increase localized stresses, whereas valley-dominated surfaces promote mechanical trapping. Kurtosis reflects asperity sharpness, influencing contact stiffness and particle embedment.

By quantifying surface morphology prior to adhesion testing, this approach establishes a controlled baseline linking microstructure to detachment forces and retention metrics, enabling repeatable, parameter-driven comparison of biomimetic surface architectures designed to mitigate regolith adhesion.

B. Wettability and Adhesion Methods

Adhesion potential can be further characterized via static contact angle goniometry. Wettability, governed by surface energy, provides an indirect indicator of particulate adhesion [21]. Surfaces exhibiting low contact angles correspond to higher surface energy, reflecting a greater tendency to attract and retain particles. Conversely, higher contact angles indicate lower surface energy and weaker intermolecular attraction, suggesting reduced particulate adhesion potential. However, contact angle does not directly characterize electrostatic forces or mechanical interlocking effects arising from surface roughness and particle morphology. These mechanisms, particularly electrostatic charging under lunar vacuum and plasma conditions, can dominate regolith adhesion behavior and therefore require direct detachment-based and charge-sensitive measurements [1, 22]. By systematically monitoring surface energy alongside quantitative adhesion force and retention testing, a more comprehensive framework can be established to identify and optimize low-adhesion, regolith-mitigating biomimetic surface designs.

C. Current Adhesion Test Methods

Existing lunar dust adhesion studies report both detachment force measurements and regolith retention metrics; however, many approaches vary in standardized control over dust deposition, environmental conditions, and quantitative repeatability. Variations in particle delivery method, humidity, electrostatic preconditioning, and vacuum level introduce significant uncertainty, limiting cross-study comparability. Additionally, inconsistent surface preparation and non-uniform particle loading complicate interpretation of measured adhesion forces, making it difficult to isolate the governing physical mechanisms.

The primary adhesion mechanisms on the lunar surface, van der Waals forces, electrostatic charging, and mechanical interlocking, directly shaped the design criteria of the current testing methodology. Since van der Waals forces are highly sensitive to separation distance and actual contact area, the framework integrates quantitative surface metrology to control and characterize micro-topography before testing. Electrostatic effects, which are intensified under lunar vacuum and ultraviolet exposure, require carefully controlled environmental conditions and repeatable particle deposition procedures to maintain consistent charge states [2, 20, 23]. Mechanical interlocking, governed by particle angularity and surface morphology, necessitates standardized loading protocols to ensure uniform particle packing and contact conditions across all samples.

The framework presented here addresses these limitations by integrating controlled deposition methods, consistent environmental conditions, pre-test surface characterization, and defined detachment procedures into a single systematic protocol. By linking measurable surface parameters to both adhesion force and retention outcomes, the methodology transitions lunar dust evaluation from qualitative comparison to a structured, repeatable, and physically grounded assessment tool. This approach enables meaningful comparison between biomimetic surface designs and supports the identification of regolith-mitigating architectures optimized for lunar environments.

V. Experimental Design Framework and Discussion

To develop a repeatable and physically representative adhesion testing framework, a structured trade study was conducted to evaluate candidate detachment and quantification methods. Primary selection criteria were lunar fidelity and ease of conduct in a typical laboratory setting.

Selection criteria for lunar fidelity were derived from the dominant lunar adhesion mechanisms: van der Waals attraction, electrostatic charging, and mechanical interlocking in vacuum environments [1, 2, 20]. Capillary forces are negligible on the lunar surface due to the lack of atmosphere. Consequently, testing methods were prioritized based on their ability to replicate dry particulate adhesion under reduced-pressure conditions.

Adhesion test methods provide metrics such as the force required to remove regolith from a surface and the fraction of dust remaining after applying a load. Residual quantification techniques considered included gravimetric mass measurement and optical profilometry volume differencing. Candidate adhesion methods evaluated included tap–tap testing, ultrasonic excitation (sonic wand), Diff-Lift (tape transfer), and centrifugal detachment [15, 16, 19, 24].

Candidate methods were assessed using weighted engineering criteria derived from lunar adhesion physics and experimental repeatability requirements. Each method was scored on a 1–5 ordinal scale for each criterion, and the total weighted score was calculated as:

$$S = \sum \omega_i r_i \tag{1}$$

where w_i represents the weighting factor associated with criterion i, and r_i is the corresponding rating assigned to the evaluated method [25]

A. Cleaning and Handling

Lunar regolith exhibits strong adhesion, making consistent handling and cleaning critical for accurate surface assessment after each trial. Various cleaning methods were considered, each with limitations: compressed air can drive particles into micro- and nanoscale features; deionized (DI) water rinses may fail to remove strongly adhered particles; isopropanol (IPA) rinses reduce surface tension and improve particle removal; ultrasonic cleaning requires specialized equipment and may alter surface properties; electrostatic removal is complex; and vacuum suction can be ineffective against tightly bound particles.

IPA rinsing was chosen for its repeatability, compatibility with mass-based quantification, and preservation of micro-texture. The method involves rinsing the sample with IPA followed by drying in a clean environment [24, 26, 27]. This procedure is reliable, suitable for alumina laminates, minimizes ionic residue, and effectively removes both particles and surface contaminants.

B. Environmental Fidelity Additions

Accurately replicating lunar dust adhesion requires careful consideration of the Moon's unique environmental conditions, including extremely low atmospheric pressure, pervasive ultraviolet radiation, and the absence of humidity [1, 2]. These factors directly influence particle-surface interactions by affecting electrostatic charging, surface energy, and particle cohesion, all of which contribute to regolith adhesion. To account for these effects, the experimental procedure will incorporate targeted conditioning of the regolith simulant prior to testing. Specifically, the simulant will be pre-baked at 100°C for 1 hour to remove adsorbed moisture and contaminants, and then stored in a vacuum bell jar to maintain a controlled, low-humidity environment and prevent reabsorption of water [20, 24]. This approach aims to replicate, as closely as practicable in a laboratory setting, the environmental state of lunar dust and minimize artifacts arising from terrestrial contamination or humidity-driven adhesion effects. By implementing these preparatory steps, the methodology ensures that subsequent adhesion measurements and particle retention tests reflect interactions that are physically relevant to lunar conditions, enabling more reliable evaluation of biomimetic surface designs and their potential for mitigating regolith adhesion.

C. Dust Deposition Method

Table 1 Regolith Deposition Method Matrix

Deposition Method	Lunar Fidelity	Repeatability	Accessibility	Primary Limitations
Aerosolization	High: Simulates lofted fine particles and electrostatic charging behavior	Moderate: Deposition mass and distribution sensitive to airflow rate and feed stability	Moderate: Requires controlled chamber and aerosol feed system[20, 27]	Low mass loading control; airborne redistribution; variability in fine fraction concentration [16]
Sieve Deposition	Moderate: Replicates gravitational settling but does not directly simulate electrostatic lofting	High: Controlled particle size bin and fixed standoff improve uniformity[24]	High: Simple setup; minimal specialized equipment	Particle cohesion/clumping; sliding-induced agglomeration[16]; limited electrostatic representation

The choice of dust deposition method is critical for establishing a repeatable and physically meaningful adhesion testing framework. Common techniques include aerosolization and sieve deposition, both offering distinct advantages and limitations with respect to lunar fidelity, repeatability, accessibility, and potential artifacts as seen in Table 1. Aerosolization can simulate the lofting of fine particles and electrostatic behavior observed on the lunar surface, achieving high environmental fidelity. However, it suffers from low mass loading control, airborne particle redistribution, and sensitivity to fine particle concentration, and it requires controlled chambers and specialized aerosol feed systems, limiting accessibility. Gravitational sieve deposition, in contrast, offers a balance of moderate lunar fidelity and high repeatability by leveraging controlled particle mass and size distribution without inducing artificial tribocharging. It is straightforward to implement, requiring minimal specialized instrumentation, and produces uniform areal loading suitable for comparative adhesion studies.

Table 2 Regolith Deposition Method Decision Matrix

Deposition Method	Lunar Fidelity (0.35)	Depostion Uniformity (0.25)	Repeatability (0.20)	Equipment Complextiy (0.10)	Total
Aerosolization	4	3	3	3	3.05
Sieve Deposition	3	4	5	5	3.55

Gravitational sieve deposition was selected to preserve the native morphology and angularity of lunar simulant particles while enabling controlled and repeatable areal loading as highlighted in the decision matrix shown in Table 2. Prior investigations of Apollo regolith samples demonstrate that particle angularity and mechanical interlocking significantly influence adhesion behavior, particularly under low-consolidation conditions [1, 2]. Sieve-based deposition minimizes artificial tribocharging and flow-induced reorientation associated with aerosol, providing a controlled baseline for comparative surface evaluation. Sieving JSC-1A to the defined particle size of <25 µm is consistent with NASA-STD-1008 recommendations for planetary dust exposure testing, improves repeatability of adhesion measurements, and replicates high adhesion regimes [1, 20].

Table 3 Risk Assessment Matrix for Regolith Deposition Methods

Adhesion Test	Primary Risk Driver	Likelihood (L)	Severity (S)	Risk Index (L×S)	Mitigation Strategy
Aerosolization	Low and inconsistent mass loading [16]; airborne redistribution	4	3	12	Closed chamber, controlled feed rate [20, 27], gravimetric pre/post checks
Sieve Deposition	Particle clumping / cohesion; sliding-induced agglomeration [16, 20]	3	3	9	Pre-bake simulant [20]; fixed standoff height; vibratory control

Risk Index = L×S
(High # = More Risk)

Low Risk
Moderate Risk
High Risk

Table 3 presents a risk matrix evaluating the two lunar regolith deposition methods discussed. Each method is assessed based on its primary risk driver, likelihood (L), severity (S), and the resulting risk index (L×S), where higher values indicate increased risk. Aerosolization is primarily driven by low and inconsistent mass loading and airborne redistribution, resulting in a likelihood of 4 and a severity of 3, yielding a moderate risk index of 12. The corresponding mitigation strategies include the use of a closed chamber, controlled feed rate, gravimetric pre/post checks, and other containment measures. Sieve deposition is characterized by particle clumping and cohesion, as well as sliding-induced agglomeration, with a likelihood of 3 and a severity of 3, producing a lower moderate risk index of 9. Mitigation measures for sieve deposition focus on pre-bake simulant, fixed standoff height, and vibratory control to minimize particle aggregation. The color-coded format in Table 3 clearly differentiates low, moderate, and high risk levels, providing a structured framework for prioritizing experimental controls and ensuring safe and repeatable regolith handling procedures.

D. Adhesion Detachment Methods

Table 4 details the Adhesion test method matrix. Operator-dependent tests, such as tap-tap methods, exhibited limited repeatability due to uncontrolled impulse magnitude and direction, making them unsuitable for precise quantitative comparisons [16]. Ultrasonic excitation has been used to assess dust removal under vacuum, but results are sensitive to alignment and acoustic field variations, which reduce reproducibility. Tape transfer provides remaining regolith metrics but does not directly quantify particulate adhesion under lunar-relevant conditions; therefore, it is used only as a

Table 4 Adhesion Method Matrix

Adhesion Test	Force Type	Quantitative	Repeatability	Lunar Fidelity	Key Strength	Primary Limitations
Tap-Tap	Low energy mechanical impulse (impact force)	Low (Mass loss %)	Low	Low-Moderate	Simple, rapid screening; minimal equipment	Uncontrolled impulse magnitude and direction; poor force resolution; high variability [16]
Diff Lift (Tape Transfer)	Adhesive transfer (post-test residual quantification)	Low (% areal coverage via ImageJ)	Moderate	Indirect	Good residual mapping; low cost; nondestructive	Does not measure adhesion force; pressure application variability [15]
Sonication (Ultra Sonic Wand)	High-frequency inertial & shear excitation	Medium-High (Retention vs amplitude, Derived adhesion force)	Low-Medium	Dynamic Adhesion Limits	Dynamic loading; non-contact; sensitive to mechanical interlocking	Acoustic field variability; not fully representative of lunar electrostatics [15, 17-19]
Centrifugal Detachment	Controlled inertial body force	High (Critical Detachment force, retention %) [16, 22-24, 28-29]	High	High (vacuum compatible; electrostatic active)	Uniform loading; scalable; force-correlated; compatible with vacuum [28-29]	Requires precision balance & speed control; assumes radial loading represents detachment physics

complementary metric rather than a primary evaluation method [15].

Table 5 Adhesion Method Decision Matrix

Method	Quantitative Output (0.35)	Lunar Mechanism Relevance (0.25)	Repeatability (0.20)	Surface Safety (0.10)	Complexity (0.10)	Total
Tap-tap	2	2	1	4	5	2.3
Diff Lift (Tape Transfer)	2	2	2	2	3	2.1
Sonication (Ultra Sonic Wand)	5	3	3	3	2	3.6
Centrifugal Detachment	5	4	5	4	3	4.45

As shown in the Adhesion method decision matrix in Table 5, centrifugal detachment was selected as the primary quantitative adhesion metric due to its ability to impose controlled and measurable acceleration loading on adhered particles. This method enables estimation of critical detachment thresholds and provides reproducible, operator-independent measurements. Compared to qualitative tap-based methods, centrifugal detachment provides a more rigorous and scalable evaluation of biomimetic surface performance, enabling simultaneous testing of multiple particles and substrates under controlled acceleration [16, 22, 24, 28, 29].

Figure 3 is a schematic of a typical centrifuge test setup for adhesion testing. The effective radial acceleration is given by:

$$a_r = r\omega^2 \tag{2}$$

where r is the rotor radius and is the angular speed (rad/s) [18, 22, 24, 28, 29]. Stepwise increments in for 10-20 s per step allow determination of detachment thresholds as a function of equivalent g-level and the deposited particle mass enables normalization of the response.

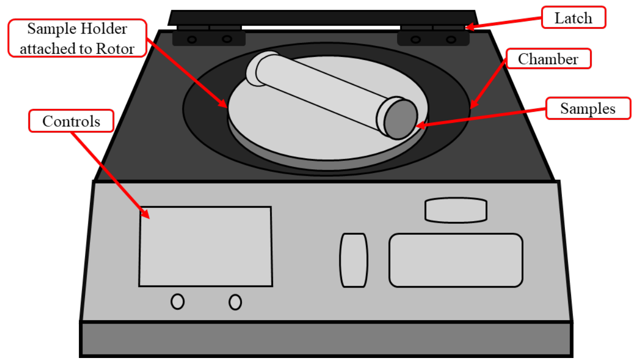

Fig. 3 Schematic of the centrifuge testing set-up designed to investigate adhesion and detachment of lunar dust simulants on test surfaces. The set-up includes a sample holder mounted on a rotor, allowing precise control of centrifugal force and environmental conditions. The system simulates the extreme conditions of the lunar surface, enabling quantitative comparisons of adhesion strength across different surface treatments [19].

Table 6 Risk Assessment Matrix for Adhesion Detachment Methods

Adhesion Test	Primary Risk Driver	Likelihood (L)	Severity (S)	Risk Index (L×S)	Mitigation Strategy
Tap-Tap	Uncontrolled impulse magnitude & direction	5	4	20	Instrumented impact device (not implemented)
Diff Lift (Tape Transfer)	Tape pressure variability	4	3	12	Standardized roller & dwell time
Sonication (Ultra Sonic Wand)	Wand alignment & acoustic field variability/ complexity	4	4	16	Fixed mounting rig & standoff calibration
Centrifugal Detachment	Rotor imbalance / RPM calibration error	2	4	8	Balanced fixtures & tachometer verification

Risk Index = L×S
(High # = More Risk)

Low Risk
Moderate Risk
High Risk

Table 6 presents a risk matrix comparing four adhesion measurement methods based on primary risk drivers, likelihood (L), severity (S), and resulting risk index (L×S). The Tap-Tap method carries the highest risk (L=5, S=4, index=20) due to uncontrolled impulse magnitude and direction; mitigation would require an instrumented impact device, though directional variability remains. The Differential Lift (Tape Transfer) method yields a moderate risk index of 12, primarily driven by tape pressure variability, which can be reduced through standardized roller application and controlled dwell time. Sonication with an ultrasonic wand results in a risk index of 16 due to wand alignment and acoustic field variability; fixed mounting and calibrated standoff distances are recommended to improve consistency. Centrifugal detachment presents the lowest risk index of 8, with rotor imbalance and RPM calibration error mitigated through balanced fixtures and tachometer verification.

The low risk index for centrifugal detachment supports the decision matrix outcome in Table 5, which identified it as the preferred method. Unlike impulse- or contact-based techniques, centrifugal testing applies a well-defined, uniformly distributed inertial force directly correlated to rotational speed and radius, enabling precise detachment threshold quantification. Reduced operator variability and straightforward calibration improve repeatability and traceability, confirming the centrifuge as the most experimentally reliable method for adhesion characterization.

E. Residual Mass Quantification

Two complementary methods were evaluated to quantify regolith retention and detachment. The first, gravimetric pre- and post-test weighing, measures mass change by comparing specimen weight before deposition and after detachment.

This approach is simple and traceable, providing a direct metric of retained or removed simulant. However, with a balance precision of 0.01 g, sufficient and consistent mass loading is required to exceed instrument resolution [16]. This reinforces the selection of sieve deposition, which enables controlled particle size distribution and repeatable mass application.

The second method, optical profilometry volume differencing, compares detailed surface scans taken before and after deposition to calculate how much particle volume remains on the surface. Because it maps the surface in three dimensions, it shows not only how much material is retained, but also where it accumulates. This helps link surface roughness features to adhesion behavior. Although this method requires additional processing, such as aligning scans and computing volume differences, it could provide clearer insight into particle distribution and retention mechanisms. Together, gravimetric and profilometric measurements offer complementary bulk and spatial characterization, strengthening the overall experimental framework.

F. Testing Flow and Data Correlation Strategy

The integrated experimental framework combines: (i) controlled cleaning and handling procedures to minimize cross-contamination and environmental variability, (ii) controlled deposition to ensure consistent and uniform simulant loading, (iii) incremental centrifugal loading to apply a well-defined and progressively increasing inertial detachment force, and (iv) multi-modal residual quantification through both gravimetric and surface profilometry techniques. Together, these elements produce repeatable, quantitative adhesion metrics with reduced operator dependence and clearly traceable force application. The incremental nature of centrifugal loading enables identification of detachment thresholds, while complementary mass and volumetric measurements strengthen result validation.

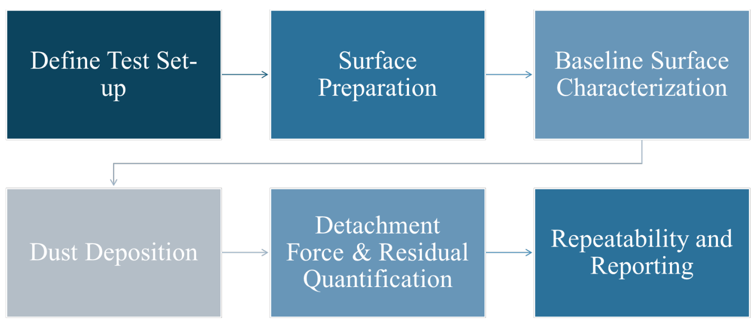

Fig. 4 A simplified version of the experimental process outlined above, presented as a linear flow chart. Each step represents a key phase in the testing process, from sample preparation and surface treatment to adhesion testing and data collection, providing a clear overview of the workflow for reproducibility and comparison across experiments.

This structured methodology visualized in Figure 4 supports direct correlation of adhesion performance with measured surface properties, including roughness parameters and wettability, allowing interpretation of how micro- and nanoscale surface features influence regolith retention mechanisms. The resulting framework is both repeatable and scalable, establishing a robust adhesion testing approach suitable for systematic evaluation and comparison of candidate lunar dust mitigation materials under controlled laboratory conditions.

VI. Conclusion

A structured and physically grounded experimental framework for evaluating lunar regolith adhesion on bio-inspired ceramic laminates has been developed. The trade study methodology integrates controlled cleaning and environmental conditioning, standardized sieve-based deposition, incremental centrifugal detachment, and complementary residual quantification through gravimetric and optical profilometry techniques. By addressing limitations identified in prior tap-based and non-standardized approaches, the framework reduces operator dependence, improves repeatability, and provides quantitatively traceable adhesion metrics while addressing risk.

Surface characterization using optical profilometry and contact angle goniometry establishes a direct link between engineered microstructural features, surface energy, and measured detachment behavior. This parameter-driven approach enables correlation between roughness metrics, wettability, and regolith retention, transforming adhesion evaluation from qualitative observation to a controlled and comparative assessment tool.

Collectively, the resulting framework establishes a repeatable, scalable, and lunar-relevant methodology for systematic evaluation of biomimetic ceramic surfaces. This foundation supports future optimization of passive dust mitigation architectures and contributes to the development of durable, low-adhesion materials suitable for long-duration lunar surface operations.

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