Investigation into Human-Assisted Cleaning Methods for Lunar Habitat Materials

Sophia Kainz*, Sohail Sharma†, Jack Schafer‡, Michiru Warren§ and Dr. Lubos Brieda¶
California Polytechnic State University, 1 Grand Avenue, San Luis Obispo, CA 93407, USA

This study investigates human-assisted regolith removal techniques for materials potentially present in a pressurized lunar habitat. Textiles and solid coupons, including OrthoFabric, glass, alumina ceramic, 6061 aluminum, polyether ether ketone (PEEK), Nextel fabric, polyurethane foam, and carbon fiber sheet, were exposed to lunar regolith simulants and subjected to multiple cleaning methods. Methods examined include brushing, blowing with hand dust blowers, wiping with dry cloths, wiping isopropyl alcohol cloths, blowing with compressed air, applying adhesive rollers, and using an ultrasonic cleaning bath. Qualitative analysis of damage to materials has been performed using scanning electron microscopy (SEM). Textiles demonstrate measurable regolith retention and visible fiber damage under SEM imaging, while hard surfaces likewise exhibit damage due to abrasion after exposure and cleaning. Cleaning performance is evaluated through analysis of optical microscope images. Results indicate that removal effectiveness varies by material type and cleaning method; however, these differences were not found to be statistically significant for either material or cleaning method.

I. Introduction

The planned return of humans to the Moon has renewed investigation into methods for mitigating exposure to lunar regolith contamination. Since the Apollo missions, lunar regolith has been known to impede hardware functionality [1]. This challenge has been studied primarily in the context of the external, near-vacuum lunar environment. In the case of prolonged human presence on the Moon, the buildup of lunar regolith inside a habitat is expected to be inevitable. Literature suggests maintaining hardware functionality through the avoidance, removal, or tolerance of regolith [2]. This research focuses on scenarios in which avoidance of lunar regolith is not possible and removal is desired. The feasibility, practicality, and effectiveness of various human-assisted cleaning methods on materials potentially present in a pressurized lunar habitat are investigated and evaluated. Evaluation of the effectiveness of cleaning methods is conducted via analysis of optical microscope images. Images taken before and after the application of a cleaning method are processed to determine the amount of regolith removed from the material during cleaning.

II. Materials and Methodology

A. Material Samples

For this set of experimental analyses, five materials were evaluated: OrthoFabric, glass, ceramic, 6061 aluminum, and polyether ether ketone (PEEK). These materials were selected in part due to their relatively light coloration, which improved contrast with lunar regolith simulants and enabled more reliable image-based analysis. Textiles such as OrthoFabric are of particular interest, as lunar regolith has been shown to embed within fabric weaves [3], and such materials are likely to be common in pressurized habitat environments. In addition to textiles, regolith poses an abrasive threat to non-textile materials including metals, polymers, and brittle surfaces such as glass and ceramics, which are also investigated in this study.

Additional materials, including Nextel fabric, polyurethane foam, and bidirectional carbon fiber sheet, were used during preliminary investigations and for scanning electron microscope (SEM) and optical microscope analysis. However, these materials exhibited poor color contrast with the regolith simulants, making them unsuitable for the image subtraction analysis method used in this study. As a result, they were not included in the final testing matrix.

*Graduate Research Assistant
†Undergraduate Research Assistant
‡Undergraduate Research Assistant
§Undergraduate Research Assistant
¶Assistant Professor

B. Regolith Simulants

The lunar regolith simulant JSC-1, developed at NASA's Johnson Space Center, was used as the primary simulant for final testing. Its darker coloration improved contrast with the selected materials, enabling more effective image analysis. A lunar mare simulant (LMS-1), produced by Space Resource Technologies, was used during preliminary investigations and for SEM and microscope analysis. The primary component of both simulants is SiO_2, consistent with the composition of actual lunar regolith [1].

Fig. 1 Lunar regolith simulants shown from left to right: Space Resource Technologies lunar mare simulant (LMS-1), Space Resource Technologies lunar highlands simulant (LHS-1), and JSC-1

C. Regolith Application

Material samples were cut into approximately 1 in. × 1 in. squares and handled using gloves to minimize contamination, as shown in Figure 2. Sample preparation and handling procedures were conducted under a laminar flow hood to reduce the risk of contamination. Lunar regolith simulant was applied to each sample in quantities of approximately 0.2–0.3 g, sufficient to fully cover the sample surface. Excess loose simulant was removed by gentle manual shaking prior to cleaning. Each cleaning method was applied until no further visible change in regolith coverage was observed.

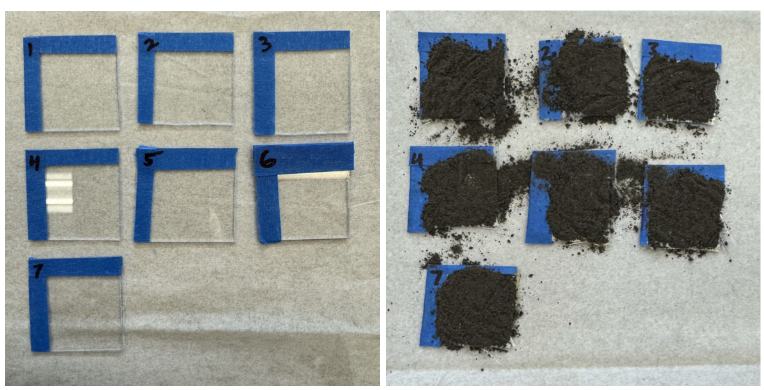

Fig. 2 Glass samples prior to regolith exposure (left) and OrthoFabric samples exposed to regolith (right).

D. Cleaning Methods

Cleaning methods evaluated in this study include brushing, hand blowing, dry cloth wiping, isopropyl alcohol wipes, compressed air, lint rollers, and sonication. These methods span direct contact removal (brushes, dry cloths, wipes, lint rollers), non-contact removal (hand blower, compressed air), and vibrational removal (sonication). The brush used was a small handheld synthetic brush. Dry cloth cleaning was performed using lint-free wipes, while isopropyl alcohol wipes consisted of lint-free wipes saturated with isopropyl alcohol. Compressed air was supplied using a standard consumer air duster, and the hand blower was manually operated. Lint rollers were used as adhesive-based cleaning tools. Sonication was performed using a small tabletop ultrasonic cleaner filled with tap water.

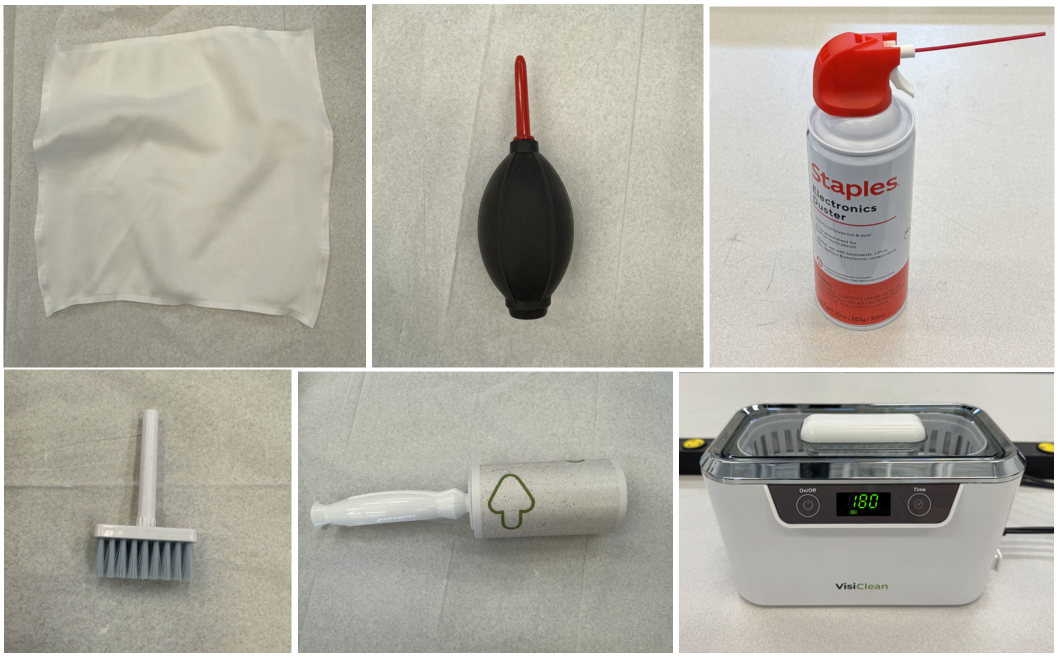

Fig. 3 Cleaning methods used in this study: (top row, left to right) dry wipe (the same material used for the wipe saturated with isopropyl alcohol), hand blower, compressed air; (bottom row, left to right) brush, adhesive roller, and sonicator.

E. Optical Imaging

The optical microscope used in this study has a resolution of 1280 × 720 pixels and an approximate horizontal field of view of 4 cm, which corresponds to a spatial resolution of ~30 μm per pixel. Imaging was conducted under the laminar flow hood to minimize contamination from ambient dust particles, as shown in Figure 4. This resolution enables visualization of particles on the order of tens of microns. Particles on the order of ~20 μm are classified as dust [2], making this microscope suitable for capturing the upper end of dust particle sizes.

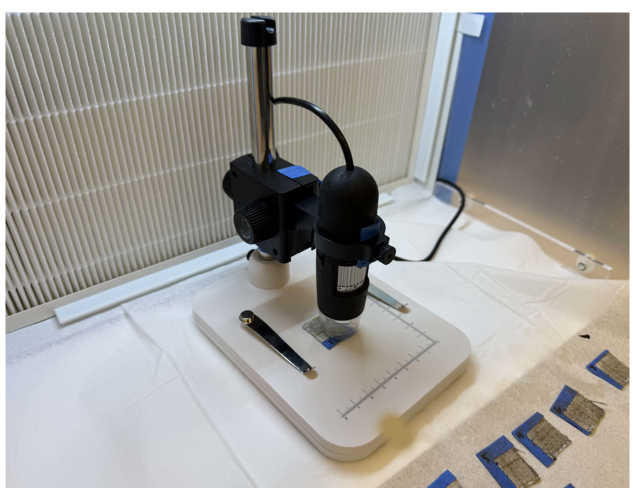

Fig. 4 Optical microscope imaging of regolith-contaminated OrthoFabric under laminar flow hood.

Sample images of OrthoFabric prior to and after regolith exposure and cleaning can be seen in Figure 5. Dust particles are large enough to be clearly imaged.

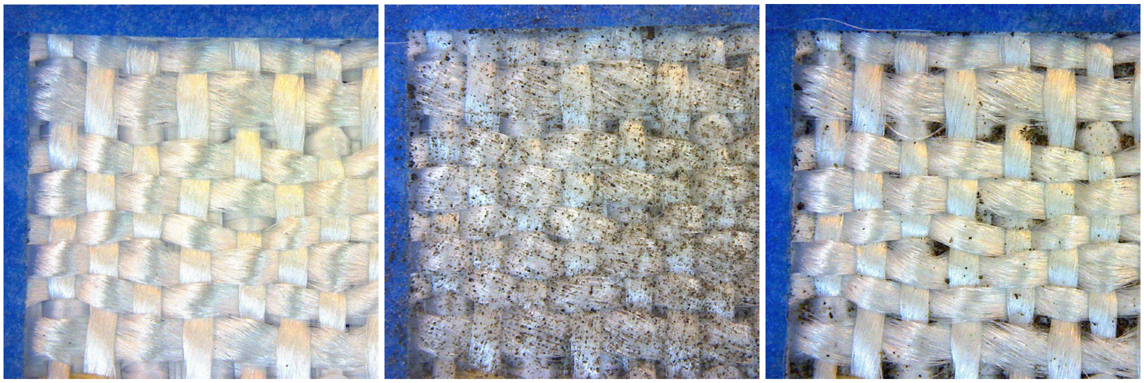

Fig. 5 OrthoFabric sample prior to JSC-1 regolith exposure (left), after regolith exposure (center), and after being cleaned with a dry cloth (right).

F. Scanning Electron Microscope Imaging

Scanning Electron Microscope (SEM) images were acquired for uncontaminated material samples and material samples subjected to various cleaning methods following regolith exposure. Material samples were cut to smaller, approximately 0.25 in. × 0.25 in. shapes and placed onto mounts as seen in Figure 6. Samples were gold-coated and analyzed using devices pictured in Figure 7. Dust particles on the order of ∼10 μm are easily imaged with the SEM used for this study. Images were produced with a field of view ranging from ∼100 μm to ∼1 mm.

Fig. 6 Mounted and gold-sputtered samples on SEM mounts. Materials from left to right are as follows: OrthoFabric, Nextel fabric, coarse polyurethane foam, fine polyurethane foam, aluminum ceramic, glass, and aluminum.

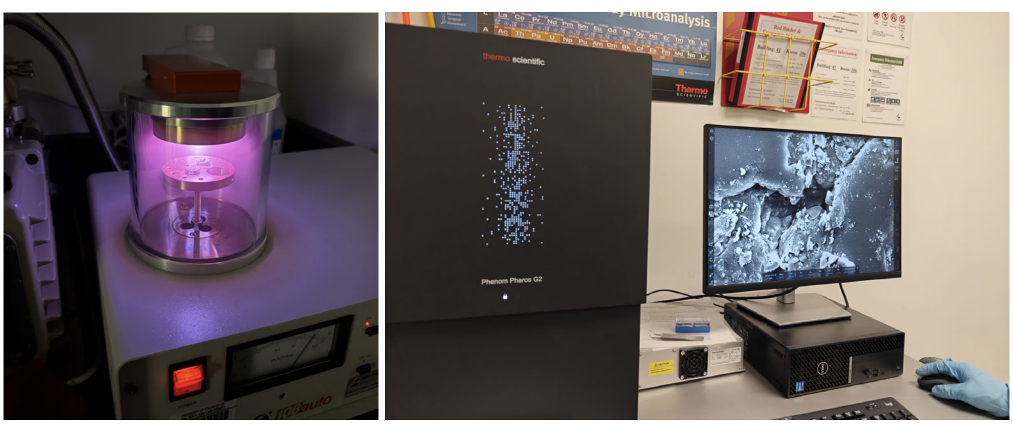

Fig. 7 Gold sputter-coater in use to gold-coat material samples (left) and Phenom Pharos SEM in use to examine regolith simulant (right).

G. Image Analysis Procedure

Images of each sample (clean, dirty, and post-cleaning) were processed using ImageJ (Fiji distribution) to quantify the percentage of regolith removed. For each sample–cleaning combination, the three images were first aligned using the tape marker as a reference. Alignment was performed using the *Linear Stack Alignment with SIFT* plugin. When the *SIFT* plugin did not work well, manual alignment was completed using a line region of interest along the tape. The aligned images were then stacked and cropped to exclude the tape and any glare artifacts. Due to this cropping step, the analyzed region of interest varies slightly between samples and cleaning mechanisms.

For analysis, the pre-processed dirty and cleaned images were converted to 16-bit grayscale, and thresholding was applied to isolate regolith particles from the sample surface. Regolith particles are represented in black while the rest of the image is white (see Figure 8). In cases where glare prevents proper grayscale thresholding, color thresholding was used before converting to grayscale. Image contrast was enhanced when necessary to improve particle visibility. The area fraction of regolith was then measured for both dirty and cleaned samples using the *Set Measurements* function in ImageJ, recording the percentage of surface area covered by regolith ($\%\text{reg}_D$ and $\%\text{reg}_C$, respectively). The percentage of regolith removed ($\%\text{reg}_R$) was calculated as

$$\%reg_R = 100 - \left(100 \times \frac{\%reg_C}{\%reg_D}\right).$$

This procedure was repeated for all material and cleaning method combinations. For aluminum samples, where the color of the regolith and aluminum were similar and glare was significant, image subtraction was performed prior to thresholding to improve regolith isolation, though this approach introduced additional uncertainty.

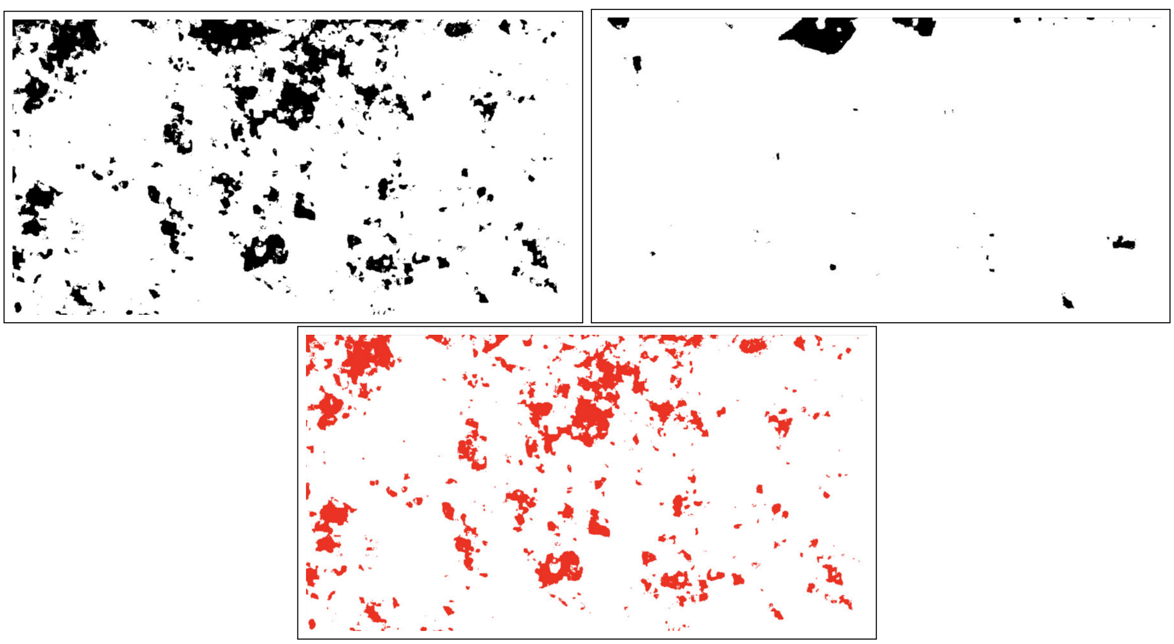

Fig. 8 ImageJ-processed optical microscope images of an OrthoFabric sample: regolith-contaminated surface (top left), surface after cleaning with compressed air (top right), and isolated regolith removed during cleaning (bottom center) obtained via image subtraction.

Figure 9 shows an example of a grayscale microscope image and the corresponding processed image. This sample was exposed to LMS-1 simulant, which contains some lighter grains that are not easily detected by the software. The grayscale thresholding works best for materials that have high visual contrast to the regolith simulant. Lighter materials like OrthoFabric and alumina ceramic provide strong contrast to the darker colored regolith such as JSC-1. Other simulant–material coupon combinations do not work as well. It is also noted that sometimes shadows within a textile weave may be incorrectly identified as regolith, leading to an underrepresentation of cleaning effectiveness.

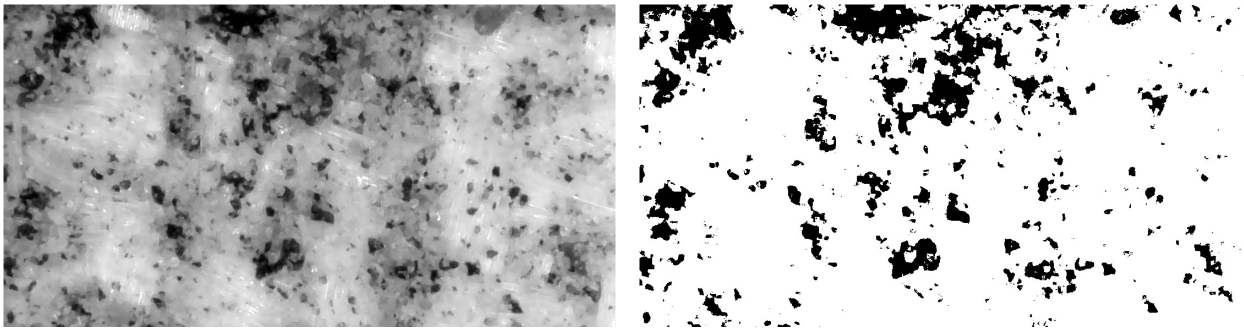

Fig. 9 Grayscale optical microscope image of a regolith-contaminated OrthoFabric sample cleaned with compressed air (left) and corresponding processed image (right).

III. Preliminary Investigations into Data Collection

Preliminary research into analysis methods to investigate the best quantitative or qualitative data provided varying results. Mass differencing, optical image subtraction, qualitative optical image analysis, qualitative scanning electron microscope (SEM) image analysis, and SEM elemental analysis were assessed. Ultimately, optical image processing was deemed the best method for acquiring quantitative data for assessing the effectiveness of regolith removal.

A. Mass Quantification

Samples were weighed before contamination, after regolith application followed by loose manual shaking, and after cleaning. Each mass measurement was averaged across three trials to reduce error associated with the scale. Mass difference was calculated using the difference between the mass measurement taken after manual shaking and after cleaning. Mass difference is expected to be positive, indicating successful removal of regolith. Differences were found to be in the 0.1 mg to 10 mg range, which were too close to the scale error of 0.5 mg to produce high–confidence results. Many mass differences recorded were negative as well, which would imply an increase in mass during regolith removal, but were instead due to the scale error being too close or higher than the order of magnitude of mass being measured.

B. Qualitative Optical Microscope Image Analysis

Optical microscope images were taken according to procedures described in Section II primarily to use the images for thresholding. However, the images are also useful to document changes or damage to the material surface that may occur during regolith exposure. Figure 10 and Figure 11 show changes to surface texture of carbon fiber samples cleaned by brush and compressed air. For carbon fiber as well as other reflective materials (including PEEK, glass, and aluminum), visible surface damage and scratching are apparent following regolith application and cleaning. Based on the increase in surface roughness, measuring change in total reflectance of samples was considered to provide quantitative data to characterize surface damage.

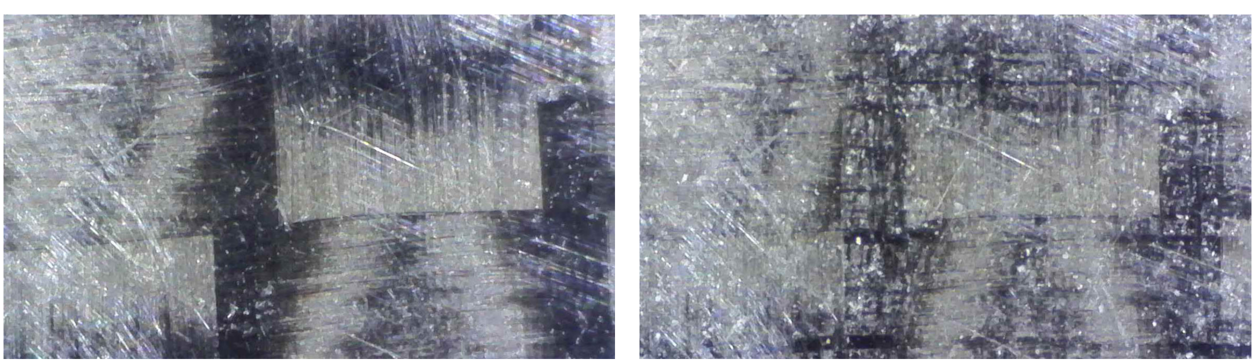

Fig. 10 Optical microscope image of an uncontaminated carbon fiber sample (left) and a regolith-contaminated carbon fiber sample cleaned with brushing (right).

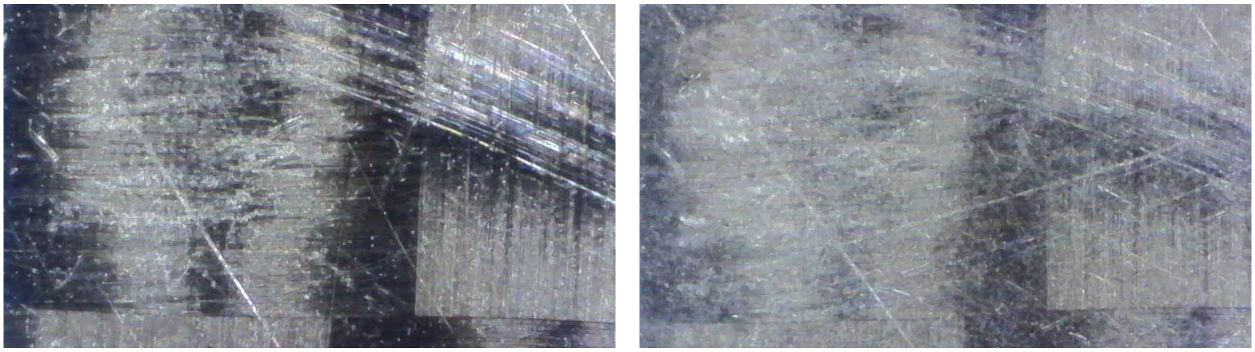

Fig. 11 Optical microscope image of an uncontaminated carbon fiber sample (left) and a regolith-contaminated carbon fiber sample cleaned with compressed air (right).

C. Qualitative SEM Image Analysis

SEM images were acquired for several material samples in three conditions: prior to regolith exposure, after regolith contamination, and following regolith removal using various cleaning methods. These images allow for investigation of micron-scale surface damage and changes as a result of regolith exposure. Figure 12, Figure 13, and Figure 14 show samples before and after regolith exposure (without cleaning). Regolith particles are seen to adhere strongly within the pores of the polyurethane foam and are easily embedded between the fibers of the OrthoFabric weave.

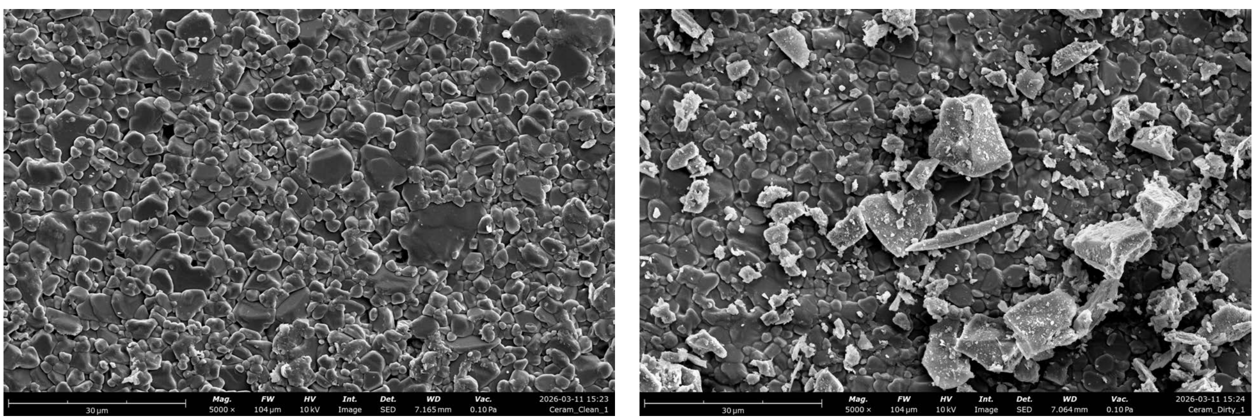

Fig. 12 SEM images at 5000 × magnification of an uncontaminated alumina ceramic sample (left) and the sample after exposure to LMS-1 regolith (right).

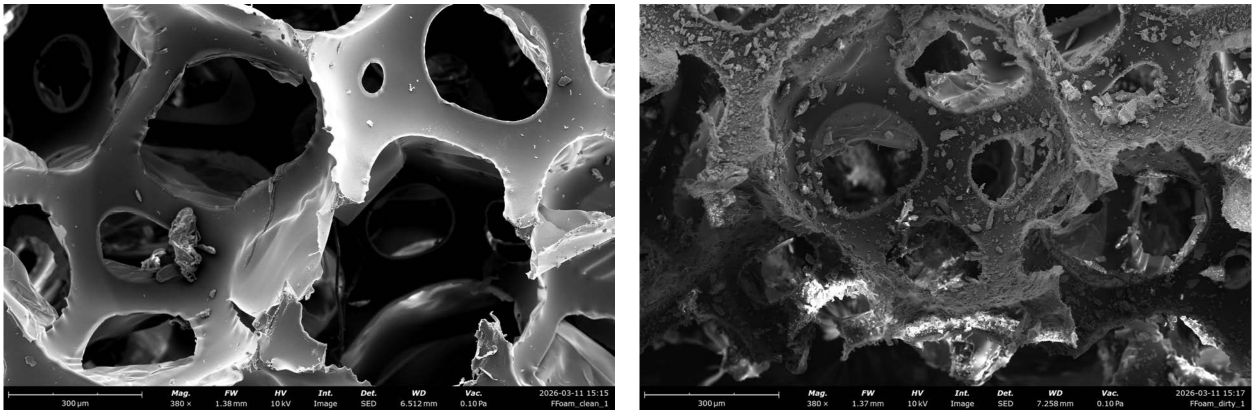

Fig. 13 SEM images at 380 × magnification of an uncontaminated polyurethane foam (left) and the sample after exposure to LMS-1 regolith (right).

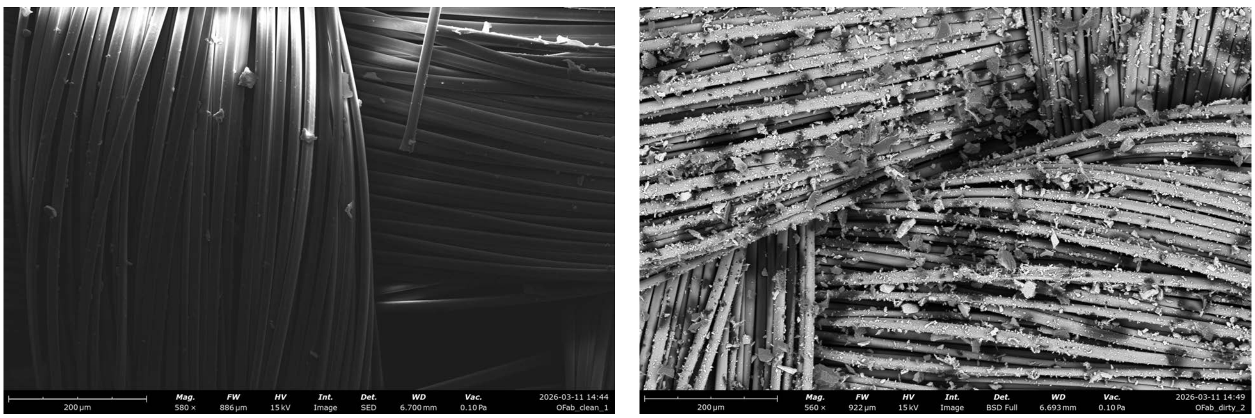

Fig. 14 SEM images at 580 × magnification of an uncontaminated OrthoFabric sample (left) and the sample after exposure to LMS-1 regolith (right).

SEM images were likewise acquired for uncontaminated material samples prior to and after being subjected to various cleaning methods following LMS-1 regolith exposure. Figure 15, Figure 16, and Figure 17 show changes that occur to OrthoFabric, aluminum, and PEEK after removing regolith via brush cleaning, compressed air cleaning, adhesive roller application, and/or sonication cleaning.

Images of OrthoFabric, as seen in Figure 15 reveal surface damage due to brushing and compressed air cleaning. Fibers in the weave appear disorganized and tangled after cleaning, with noticeable regolith adhesion and wear on the fibers. The sonication-cleaned sample seen in the lower right of Figure 15 appears most similar to the uncontaminated control sample shown in the top left. The sonicated fabric, like the control sample, shows relatively organized fibers with minimal regolith adhesion. This could indicate that sonication may be more effective and less abrasive than the other evaluated cleaning methods for textiles. However, it is noted that the SEM's field of view is small compared to the entire sample area, and the images are potentially not representative of the whole sample. Imaging and evaluation across multiple areas of the sample would improve confidence in conclusions.

Figure 16 and Figure 17 show surface damage due to regolith exposure and cleaning, compared to uncontaminated control samples for aluminum and PEEK coupons. Scratches, indents, and residual particles not visible in the control are visible in all the materials subjected to contamination and cleaning.

The lower right image in Figure 17 shows a PEEK sample after cleaning with an adhesive roller and exhibits damage not observed in any other sample. The damage is possibly adhesive residue, introducing a new and likewise unwanted contaminant. This kind of contamination was not observed using the optical microscope, and would not appear during image thresholding. This demonstrates the value of SEM in revealing surface damage and contamination that are not detectable through other imaging methods.

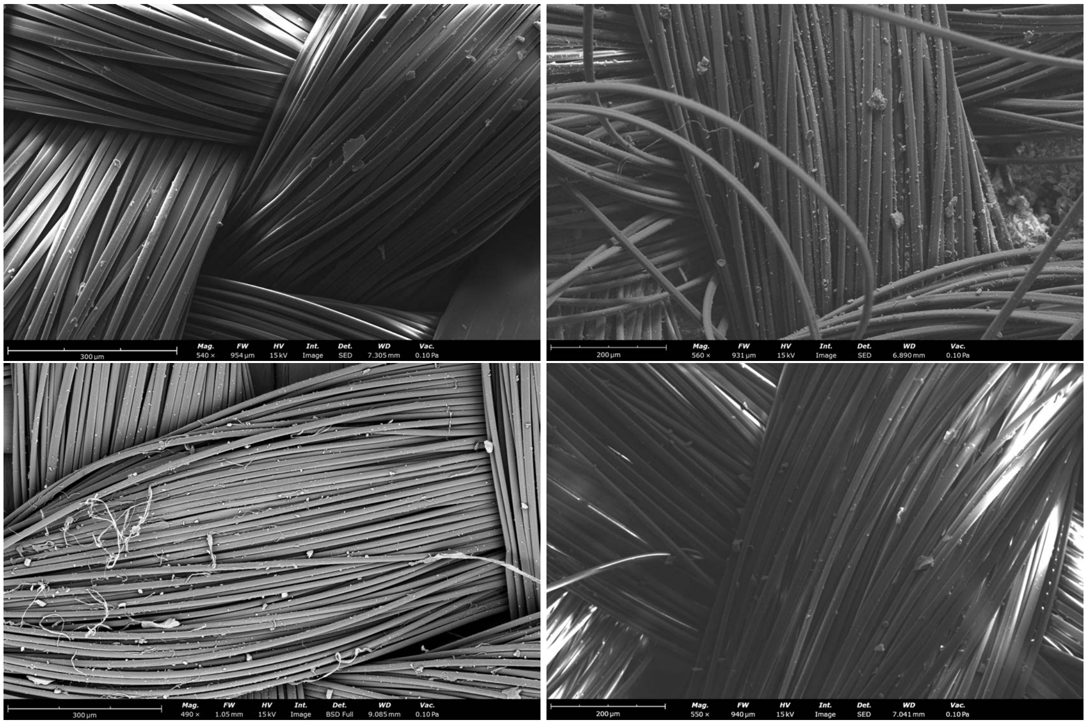

Fig. 15 SEM images of OrthoFabric samples at 490 × magnification: uncontaminated control (top left), brush cleaned (top right), cleaned with compressed air (bottom left), and sonicator cleaned (bottom right).

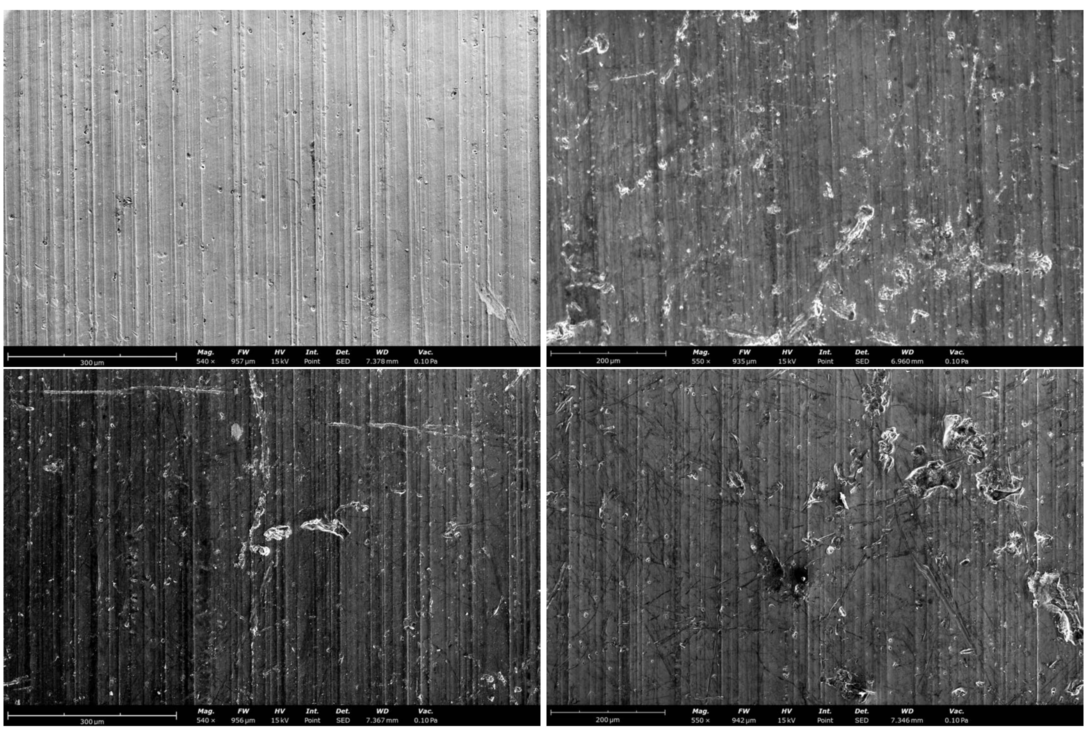

Fig. 16 SEM images of aluminum coupons at 540 × to 550 × magnification: uncontaminated control (top left), brush cleaned (top right), cleaned with compressed air (bottom left), and adhesive roller cleaned (bottom right).

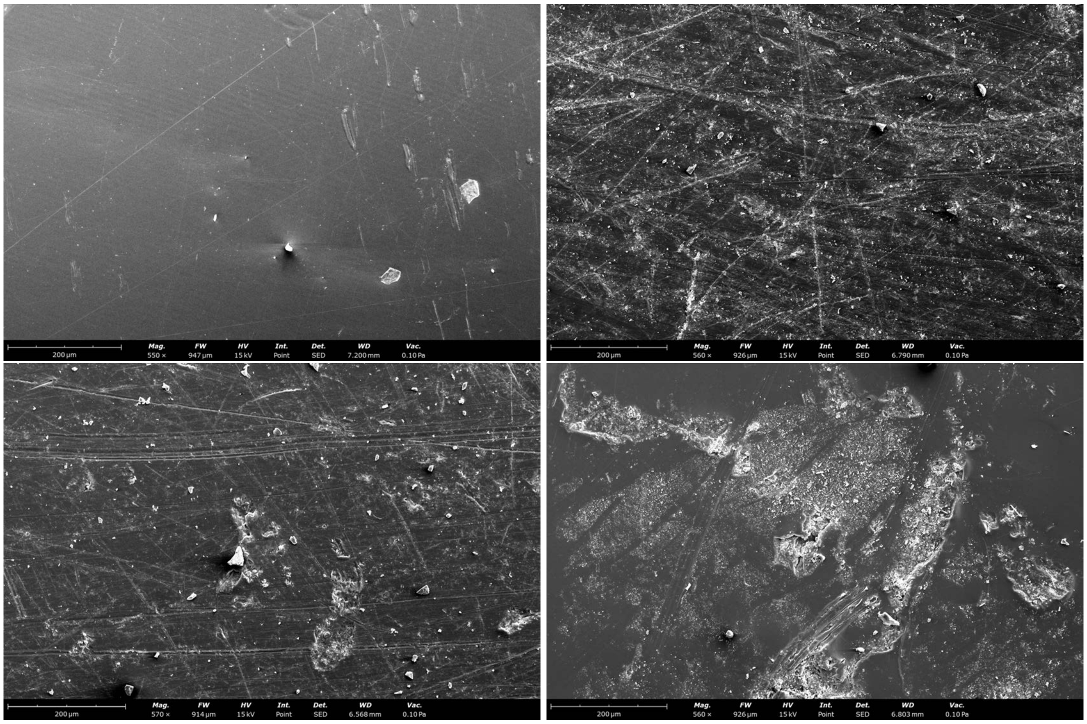

Fig. 17 SEM images of PEEK samples at 550 × to 570 × magnification: uncontaminated control (top left), brush cleaned (top right), sonicator cleaned (bottom left), and adhesive roller cleaned (bottom right).

D. SEM Elemental Analysis

The Phenom Pharos SEM has an elemental analysis feature that was used for several contaminated samples to verify the presence of regolith. Elemental analysis, as shown in Figure 18, for a contaminated aluminum coupon reveals a strong presence of oxygen and silicon. The composition of LMS-1 used in this image is 48.22% SiO_2 by weight, indicating that the red-colored region in Figure 18 is likely regolith simulant particles.

Image subtraction using SEM elemental color maps, rather than optical microscope images, may be a feasible approach for determining sample area coverage by regolith. However, analysis of such a small image area (on a scale on the order of ~10 μm to ~100 μm) would not be adequately representative of coverage of the whole sample.

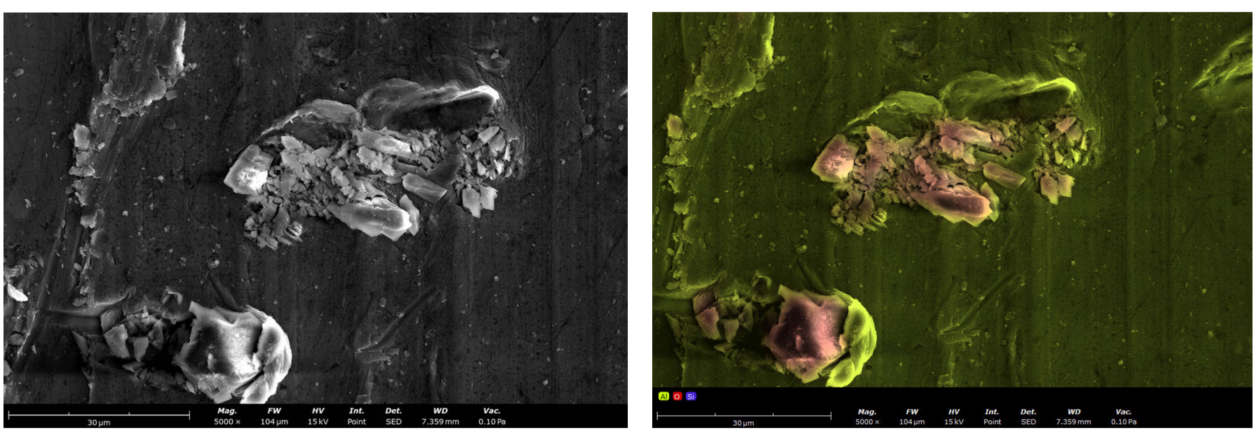

Fig. 18 Regolith particles on an aluminum surface at 5000 × magnification with standard SEM imaging (left) and corresponding elemental composition map (right).

IV. High-Contrast Testing Matrix and Statistical Analysis

Optical image processing on materials with high color contrast to regolith was determined to be the most effective method for acquiring quantitative data. Light-colored materials were selected, as shown in Table 1, that would provide high contrast to JSC-1 regolith simulant and simplify the thresholding process during image analysis in ImageJ.

Table 1 Materials and Cleaning Methods Used for Image Analysis

Materials	Cleaning Methods
OrthoFabric	Brush
Glass	Hand Blower
Ceramic	Dry Cloth
Aluminum	Isopropyl Alcohol Wipes
PEEK	Compressed Air
	Lint Roller
	Sonicator

Using the materials and cleaning methods described in Table 1 and the image processing procedure described in Section II.G, percent regolith removal values were calculated for all 35 combinations of materials and cleaning methods. Image processing for aluminum proved to be difficult due to glare, which has introduced uncertainty for testing levels including aluminum. Table A.1 in the Appendix contains the full set of measured percent regolith removal values. A full factorial two-way analysis of variance (ANOVA) was conducted using JMP Student Edition to evaluate whether cleaning effectiveness varied significantly by material or cleaning method (see Table 2). The p-value (denoted as Prob > F) in Table 2 for both material and cleaning method is much higher than the typically accepted value of 0.05 for statistical significance.

Table 2 Effect Tests from Two-Way ANOVA

Source	Degrees of Freedom	Sum of Squares	F Ratio	Prob > F
Material	4	386.50693	1.4650	0.2439
Cleaning Method	6	699.72897	1.7681	0.1485

Several trials have been performed for each material–method combination, but only one trial's images have been fully processed. The current data from the single trial in Table A.1 has insufficient number of replicated trials to establish statistical significance. Additional replicates are required to improve statistical power and allow for stronger conclusions.

V. Future Work and Conclusion

These results are preliminary and are not yet sufficient to determine the optimal cleaning method for each material. While differences in cleaning effectiveness were observed, additional test replicates are needed to improve statistical power and determine whether these differences are significant. This work demonstrates that ImageJ thresholding provides a practical method for quantifying regolith removal from material surfaces, at least for more matte materials and suitable high-contrast material–regolith combination. SEM imaging has successfully revealed micron-scale abrasive damage as well as residual contamination, but its limited field of view makes it less suitable for evaluating overall cleaning effectiveness across an entire sample.

Acknowledgments

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A. Additional Data

Table A.1 Measured percent regolith removal for each material and cleaning method. Values were obtained from ImageJ-based analysis of optical microscope images taken before and after cleaning.

Material	Cleaning Method	Percent Removed (%)
OrthoFabric	Brush	90.82
	Hand Blower	68.62
	Dry Cloth	84.84
	Isopropyl Alcohol Wipes	83.79
	Compressed Air	99.48
	Lint Roller	87.87
	Sonicator	88.79
Ceramic	Brush	94.50
	Hand Blower	99.72
	Dry Cloth	99.29
	Isopropyl Alcohol Wipes	99.77
	Compressed Air	99.00
	Lint Roller	86.06
	Sonicator	92.10
Glass	Brush	97.64
	Hand Blower	95.41
	Dry Cloth	98.77
	Isopropyl Alcohol Wipes	97.84
	Compressed Air	98.78
	Lint Roller	89.33
	Sonicator	82.64
PEEK	Brush	87.77
	Hand Blower	98.86
	Dry Cloth	79.58
	Isopropyl Alcohol Wipes	98.40
	Compressed Air	99.50
	Lint Roller	70.31
	Sonicator	98.09
Aluminum	Brush	95.58
	Hand Blower	98.65
	Dry Cloth	98.34
	Isopropyl Alcohol Wipes	99.48
	Compressed Air	95.34
	Lint Roller	89.51
	Sonicator	72.07