Determination of Percent Area Coverage of Lunar Simulant on a Surface and Observations of Fairy Castle Structures

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With NASA's goal of returning humans to the Moon, it has become increasingly important to understand the impact of lunar regolith on spacecraft systems. The ability to measure the level of dust coverage on a surface is essential. Developing an accurate technique to determine percent area coverage is challenging due to the unique and complex layering of the dust particles on the surface, creating fairy castle structures that form complex towers, bridges, and buttresses using the smallest of dust particles as building blocks. For this study, these structures have been simulated using a unique dust distributor device and imaged with a scanning electron microscope. The results show the dusted surface's complex topology, thus demonstrating the difficulty with determining the percent area of dust coverage. Implications for dust buildup on spacecraft, even at the microscopic level, can include degraded heat transfer and altered optical properties, making continuation of this research critical to support future human exploration of the Moon.

I. Introduction

Lunar dust and the problems it can cause for lunar exploration missions have become important points of discussion. With the rise of the National Aeronautics and Space Administration's (NASA's) Artemis Program to return astronauts to the surface of the Moon, along with efforts of other countries and commercial entities, the discussions surrounding lunar dust and the optimal ways to manage it are becoming critical. The Johnson Space Center's (JSC's) Lunar Dust level sensor and Effects on Surfaces (LDES) project is currently studying the effects of lunar dust on radiator systems, and how heat transfer changes through a dusted surface to space environment conditions. As a part of this endeavor, a correlation between a known dust area density, or loading (in mg/cm^2), and the dust percent area

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coverage (PAC) is being developed to present experimental results. Two methods for converting dust loadings to PACs were evaluated; both involve digital image processing.

One of the major challenges in trying to define what "percent area coverage" truly means stems from the development of complex structures when dust is deposited on a surface. Fairy castle structures are towering stacks and bridges of tiny dust particles that can form when the particles of dust are small enough, and falling slowly enough, that they stick to one another by only their Van der Waals forces [1]. These intermolecular forces must be stronger than the weight of the particles; therefore, particles can be held together by only one or two points of contact, rather than the typical three or more required for common "gravel-packing." When these structures form, gaps and channels may arise on a dusted surface such that, despite a larger dust loading, the surface appears to not be fully covered/occluded. In addition, a surface that looks completely covered when viewed from the top may have bare spots when viewed from a different angle. These structures also impact the way heat is transferred from the surface to the environment. The LDES project is interested in these structures particularly because they affect the surface topology of dusted surfaces, and therefore can have an impact on both heat transfer and percent area coverage determinations.

II. Research Techniques

The current research hypothesizes that lunar regolith, containing dust particles with very fine fractions sized in the micrometer range, will deposit onto space vehicles/surfaces when activities disturb the local environment such as vehicle landing, drilling, Extravehicular Activities (EVAs), etc. For this study, a unique dust distributor device was repurposed from that used in a previous Mars dust study [2]. This device was designed to allow dust to be uniformly applied to test surfaces, in this case microscope slides and Scanning Electron Microscope (SEM) stubs. The SEM stubs were proposed to visualize the dust structure under the significant magnification achievable with a scanning electron microscope but were also tested for use as a sample method for PAC calculation. As described in Ref. [2], mass measurements for the dust loading were made using the microscope slides and a precision scale from Mettler Toledo (Model MS1003TS/A00). Figure 1 shows the placement of the slides and stubs on the test platform. For each numbered position on the test platform, there were two microscope slides—A and B. The two slides were sampled together to be considered duplicates and should have approximately the same dust loading value. Two lunar dust simulants were studied in this research: Lunar Highlands Simulant-1D (LHS-1D) and NASA/USGS (United States Geological Survey)-Lunar Highlands Type-4M (NU-LHT-4M).

Once the slide and stub test articles were prepared using the procedure described in Ref. [2], two methods to measure dust coverage as a percentage of surface area covered/obscured from a top-down view were employed. First, Texas A&M University (TAMU) developed a digital imaging technique using an XIMEA XiC camera with a resolution of 12 megapixels, a custom Light Emitting Diode (LED) lighting arrangement, and a custom 3D-printed

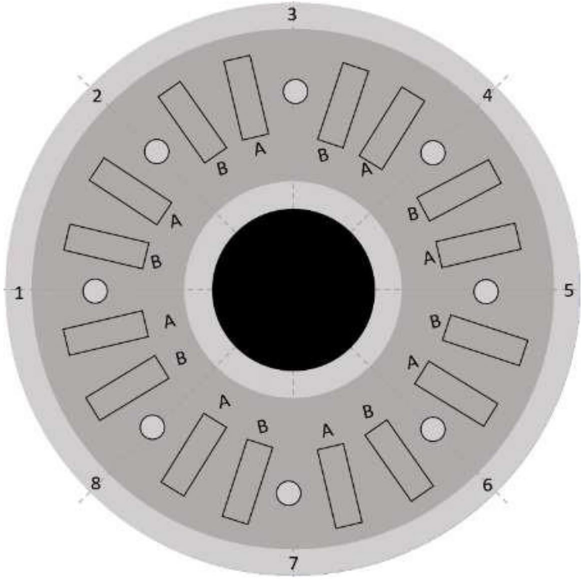


Fig. 1 Scale model (1:3) of the test platform setup for dust deposition. Rectangles represent microscope slides and circles represent SEM stubs in their holders. For each numbered location on the test platform, there is a microscope slide A, a microscope slide B, and an SEM stub. The black hole in the middle is the location of the dispersion devices as described in Ref. [2].

acrylic enclosure, also further described in Ref. [2]. The samples created on standard 2.53 cm by 7.62 cm microscope slides were imaged with the camera setup and then processed using Python and OpenCV. The cropped images were then translated and rotated prior to a Contrast Limited Adaptive Histogram Equalization (CLAHE) routine being performed. Otsu's Binarization method was used to automatically determine the threshold value. The white pixel values were summed and compared to the total pixel value of the image to give the percent coverage.

An alternate method was evaluated that also used digital image processing at JSC. This technique created images initially from the SEM sample stubs and then from samples on microscope slides. To evaluate PAC of SEM sample stubs, a photography workstation was used to capture high resolution Tagged Image File Format (TIFF) digital images of the SEM stub surfaces. The images were then processed with ImageJ (1.54f); each image was enhance-contrast-processed using 0.35% saturated pixels. The enhanced images were cropped to include only the circular region of interest and converted to 8-bit TIFF images. An 11-mm diameter mask was drawn in the center of the 12-mm diameter stub face to avoid glare from the stub’s edge, and the lower threshold was then adjusted manually to create highlights of the dust particles on the black carbon tape background. The PAC per sample was then extracted from these analyzed data where the total area of the detected particles is divided by the total area of the 11-mm diameter mask.

Initially, JSC only performed PAC analyses with the SEM stubs and TAMU only evaluated the microscope images. It was determined from the preliminary results, as well as inspection of the images, that the SEM samples and microscope slide samples were inconsistent and could not be reliably compared. To study this finding further, the SEM and microscope slide images were swapped between JSC and TAMU so that comparison of each PAC calculation method could be completed with both groups analyzing the same samples.

In addition to the PAC evaluations, the stubs were imaged using the SEM to visualize fairy castle structures. The samples were imaged in a Zeiss SUPRA 55VP scanning electron microscope at a pressure of 3×10^{-6} Torr (4×10^{-10} atm) and a working distance of about 3 mm. The working distance is defined to be the distance between the pole piece of the electron microscope and the sample. This working distance was chosen due to the low energy of the electron beam, and the minimum magnification level needed to perform broad surveys over the samples. Because the lunar dust simulants were weak electrical conductors, high magnification imagery from the electron microscope was difficult. Care was taken during image acquisition to avoid negative charge build-up on the sample without the use of a conductive coating. At a fixed energy of 1.00 keV, the electron beam did not disturb small particles in each field of view. To search for fairy castle structure formation, a broad survey at 100x magnification on different areas of the SEM sample was initially performed. At this magnification, small well-defined structures were evident as shown in Fig. 2. Then, the magnification was adjusted to bring the small particles into focus while occupying most of the field of view as shown in Fig. 3. This was repeated for several different locations per SEM sample stub.

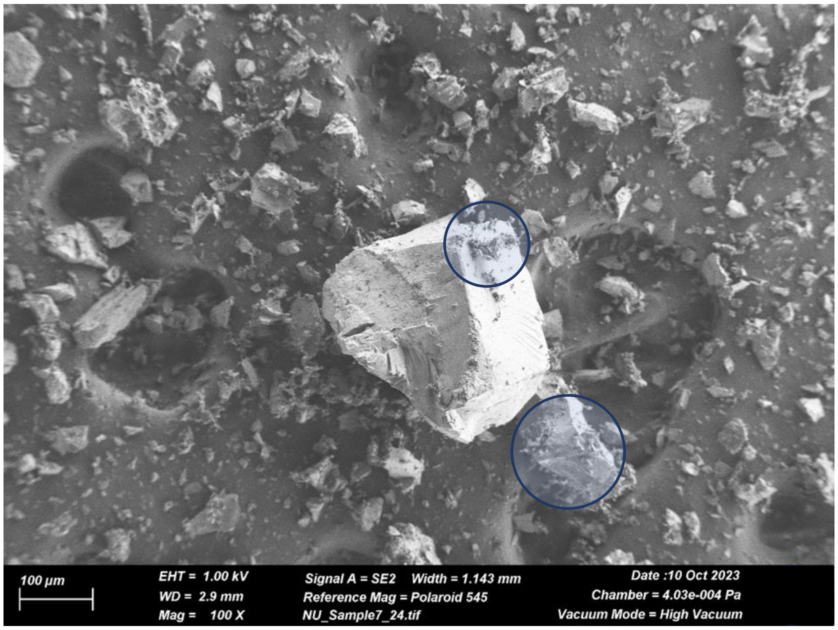
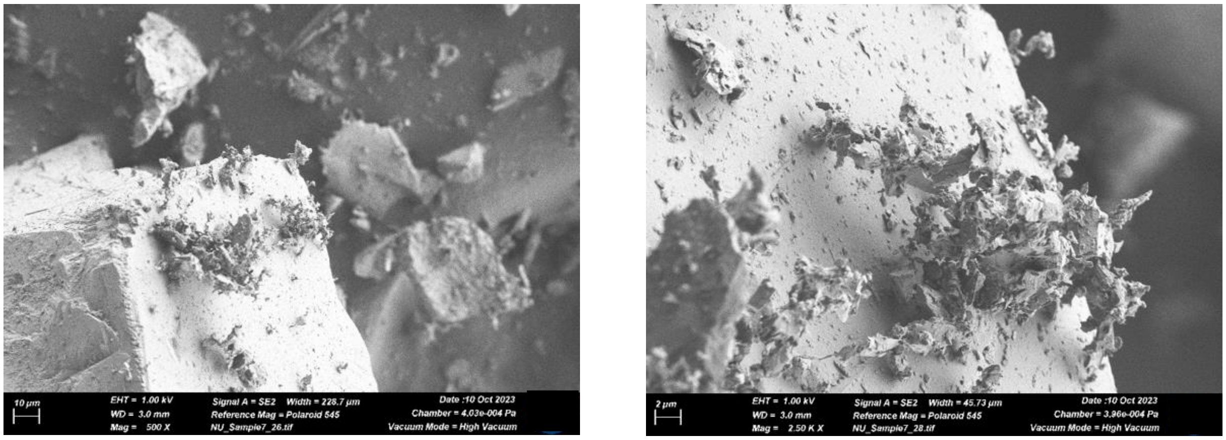


Fig. 2 SEM image at 100x magnification of NU simulant particles. Note: there are small, well-defined fairy castle structures within the circled regions. The porous double-sided carbon tape is evident in the entire background of the image.



(a) **(b)**

Fig. 3 SEM image of a region showing promise of fairy castle structures; (a) is at 500x magnification and (b) is at 2500x magnification.

III. Results

Percent area coverage was calculated for the SEM stub samples as well as the microscope slide samples by both JSC and TAMU. Images of the SEM stubs and microscope slides, as well as preliminary results, indicated that the two sample types (stubs vs slides) were not similar enough to yield comparable nor consistently reliable results. The PAC values derived from the SEM stub samples showed no distinguishable relationship to the dust loading. The data appeared to be random and inconsistent between the two evaluators. Due to these findings, the SEM stubs were no longer considered a reasonable method for calculating PAC. Therefore, focus shifted solely to the microscope slide data for evaluating PAC.

For the microscope slide samples, the data are presented in four plots for comparison. Percent area coverage as a function of dust loading is provided in Fig. 4a-d and includes data for LHS-1D[1] and NU-LHT-4M[2] dust simulants from both JSC and TAMU. For Figs. 4c and 4d, the A and B microscope slide data were combined into one larger dataset, since in Figs. 4a-4b it was noticed that the A and B datasets were very similar. A non-linear relationship between PAC and dust loading is indicated from the data. These data may be used in future research to convert dust loading values to PAC values without requiring complex image analysis. Although the data differ somewhat between JSC and TAMU, as well as for the two different dust types, the trend is generally consistent. A model of the same form as the Michaelis-Menten enzyme kinetics equation was selected as a fit for these data due to the similar shape of such models and the analogy that can be made between enzyme kinetics and dust deposition. The Michaelis-Menten equation suggests that the reaction rate will decelerate with increasing substrate concentration when enzyme concentrations are small—meaning that the reaction rate will be limited by the amount of enzyme available to bind substrate, and it will approach the maximum rate quickly at low substrate concentrations. Applied to dust deposition, a model of this form suggests that the rate of percent area coverage decelerates with increasing dust loading assuming a fixed surface area—meaning that the percent area coverage will be limited by the surface availability, and it will approach full coverage quickly at low dust loadings. R^2 values for the curves were also calculated to better understand the fits, and no significant differences for R^2 values for TAMU vs JSC, or NU vs LHS, curve fits were observed. The range of R^2 values for all the data was 0.587 to 0.897 with an average value of 0.748.

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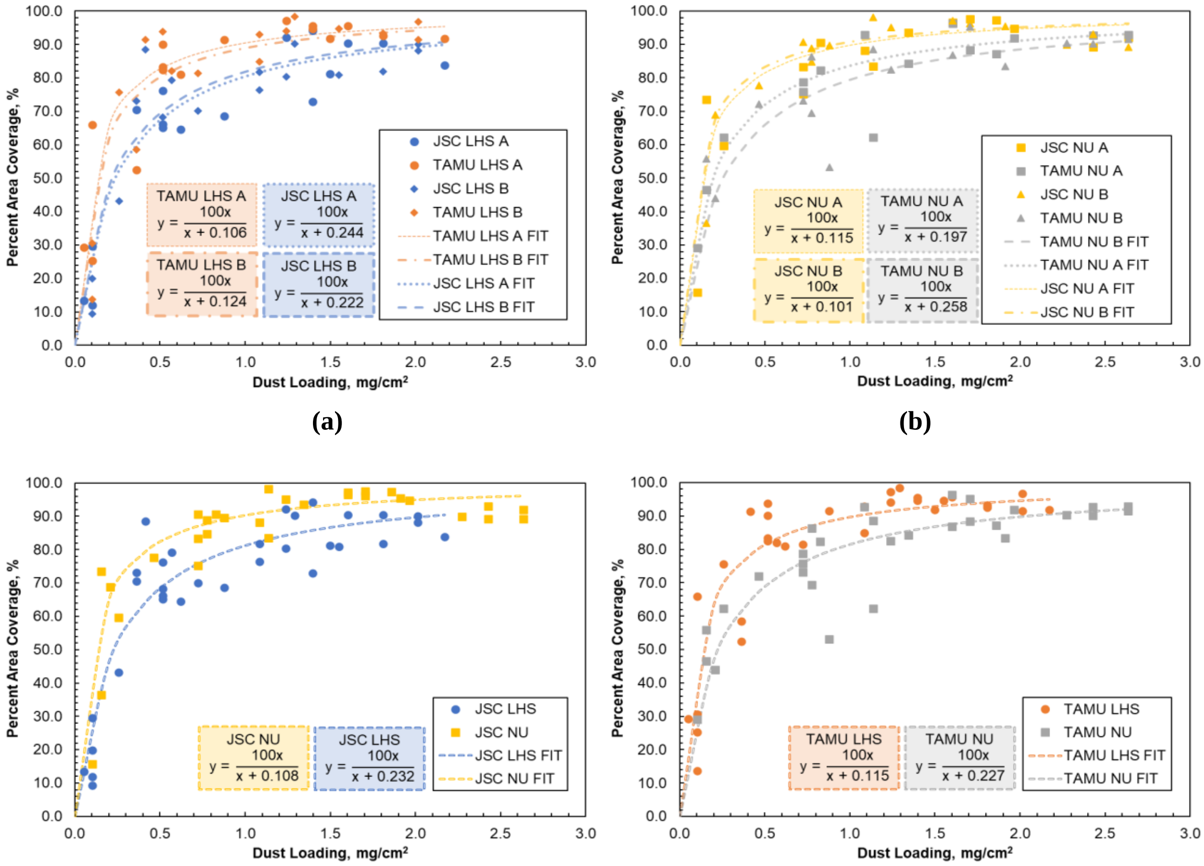
[1] For the authors' convenience, this paper at times refers to LHS-1D as 'LHS' and at other times as 'LHS-1D.' Unless otherwise noted, the reader should construe each usage of 'LHS' to refer to 'LHS-1D.' Questions on this or other matters within this paper can be directed to emma.j.goodman@nasa.gov.

[2] This paper at times refers to NU-LHT-4M as 'NU' and at other times as 'NU-LHT-4M.' Unless otherwise noted, the reader should construe each usage of 'NU' to refer to 'NU-LHT-4M.' Questions on this may be directed to the email provided above.



(a)

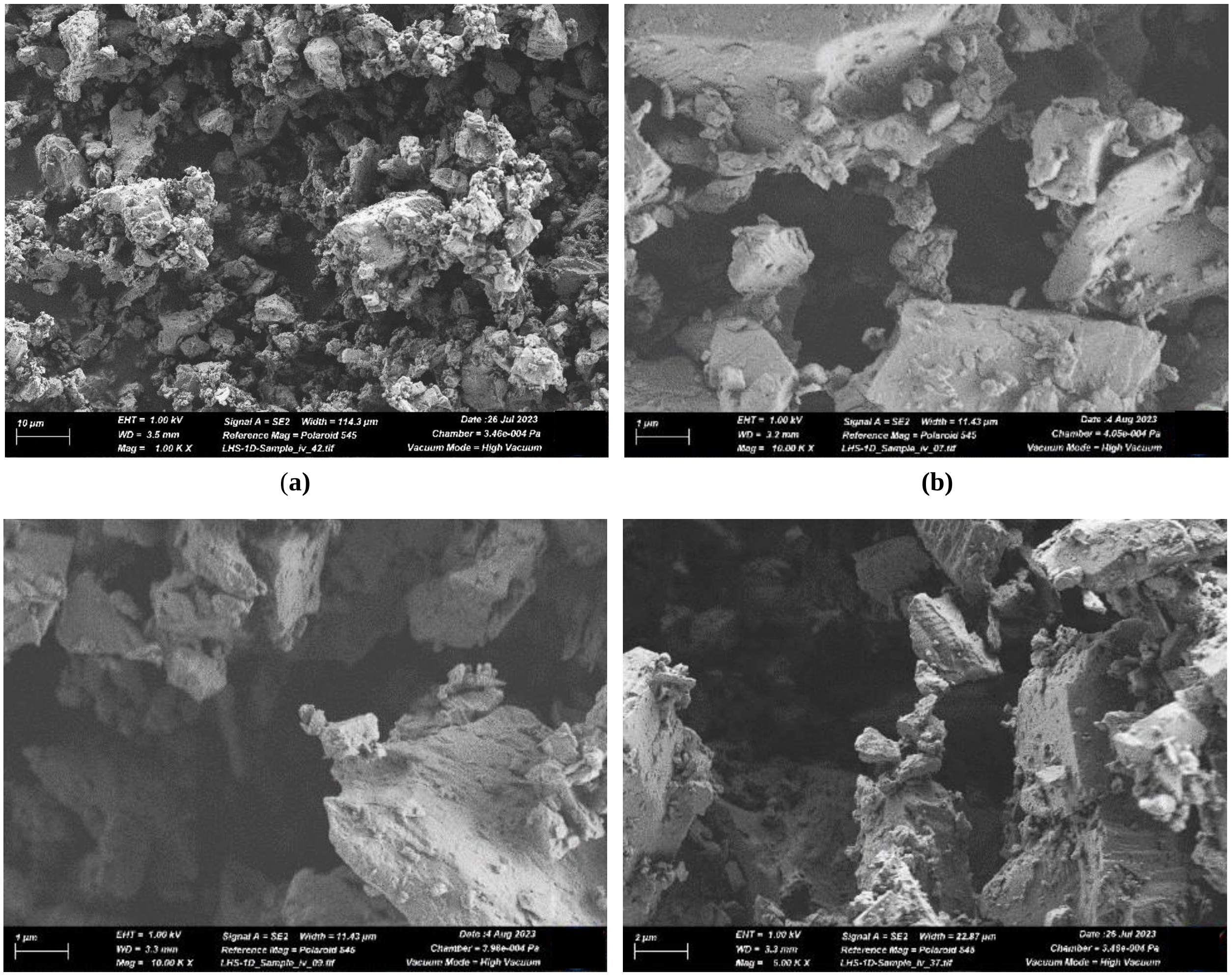
(b)

(c)

(d)

Fig. 4 Calibration data for PAC from microscope slide samples. (a) shows all LHS dust data from both institutions; (b) shows all NU dust data from both institutions; (c) shows all LHS and NU dust data produced by JSC, with the A and B data sets combined; and (d) shows all LHS and NU dust data produced by TAMU, with the A and B datasets combined.

An additional goal of this research was to visually characterize fairy castle structures that form during deposition of the lunar simulants. A preliminary experiment, wherein SEM stubs were dusted with LHS-1D simulant by hand, showed the first signs of fairy castle structures forming on test surfaces even with small dust loads. These images are presented in Fig. 5. After successfully demonstrating the technique to visualize the surface structure, the experiment was further developed, and the SEM stubs were put in the scanning electron microscope to image the fairy castle formations constructed through use of the dust distributor.



(a) **(b)**

(c) **(d)**

Fig. 5 SEM images at varying magnifications of LHS-1D where simulant was applied by hand to the SEM stub surface: (a) is a region at 1,000x magnification; (b) is one region 10,000x magnification; (c) is a different region at 10,000x magnification; and (d) is a region at 5,000x magnification.

Both LHS and NU simulants exhibited fairy castle structure formations at a variety of sample dust loadings. LHS-1D images are presented in Fig. 6 through Fig. 8 and show the intricate lacy structures that arise for simulants of this grain size. NU-LHT-4M images are presented in Fig. 9 through Fig. 11 and show similar structures with grain sizes up to an order of magnitude larger than in the LHS dust. These images are visual evidence that fairy castle structures can form under Earth conditions when particles are small enough; it stands to reason that under lunar conditions (e.g. gravity that is 1/6 that of Earth, dust particles conditioned by UV radiation, electron deposition, plasma interaction, etc.), fairy castling may be prevalent even with little dust present or larger particle sizes [1]. Therefore, fairy castle structures may make up the entire outermost coating of dust on the Moon's surface, and the particles may be disturbed, lofted, and then adhere to any material that comes into contact with them. A very light coating of dust on a surface may be nearly non-visible to the eye (with particles <40 micrometers), but the dust is still present. This could cause problems for space vehicle systems, such as for heat rejection due to a thermally resistant layer created by the dust buildup.

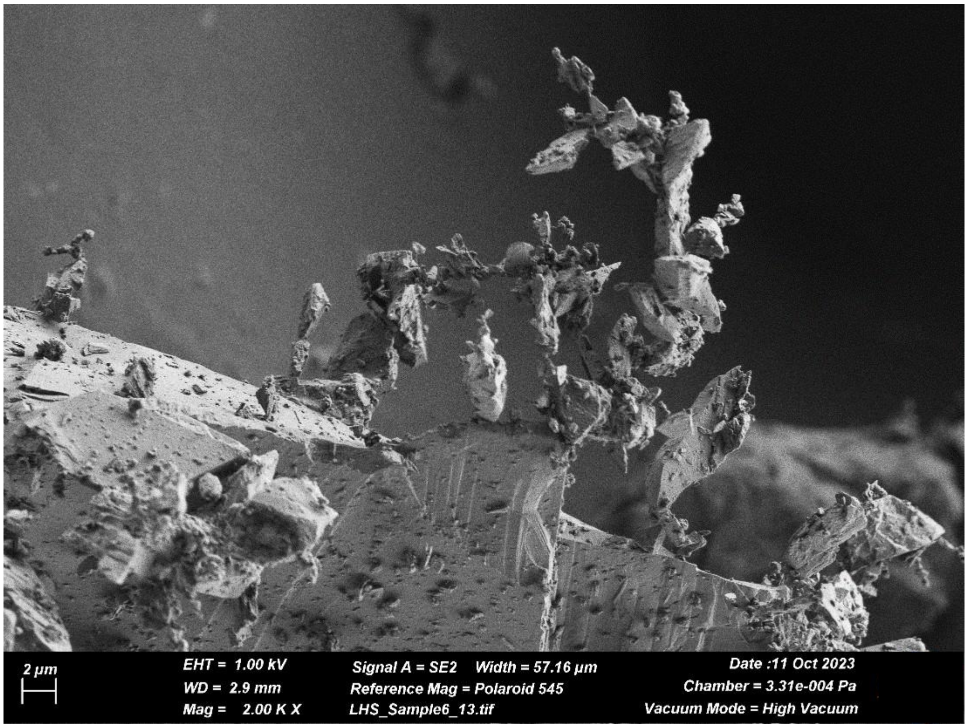


Fig. 6 SEM image at 2,000x magnification showing LHS-1D forming fairy castle structures at a loading of 0.517 mg/cm^2.

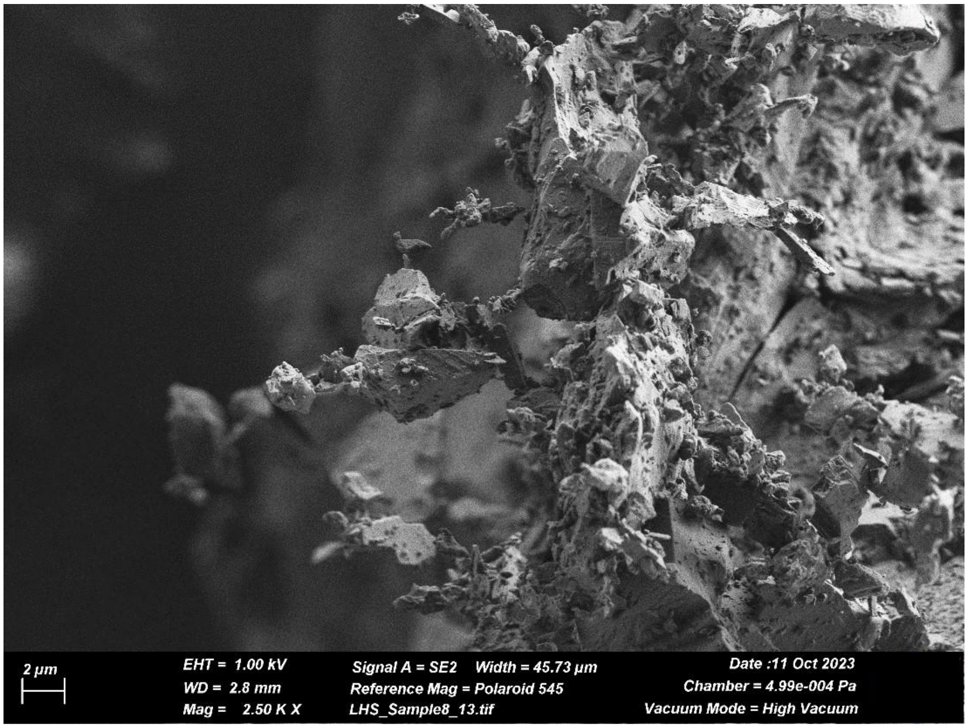


Fig. 7 SEM image at 2,500x magnification showing LHS-1D forming fairy castle structures at a loading of 0.672 mg/cm^2.

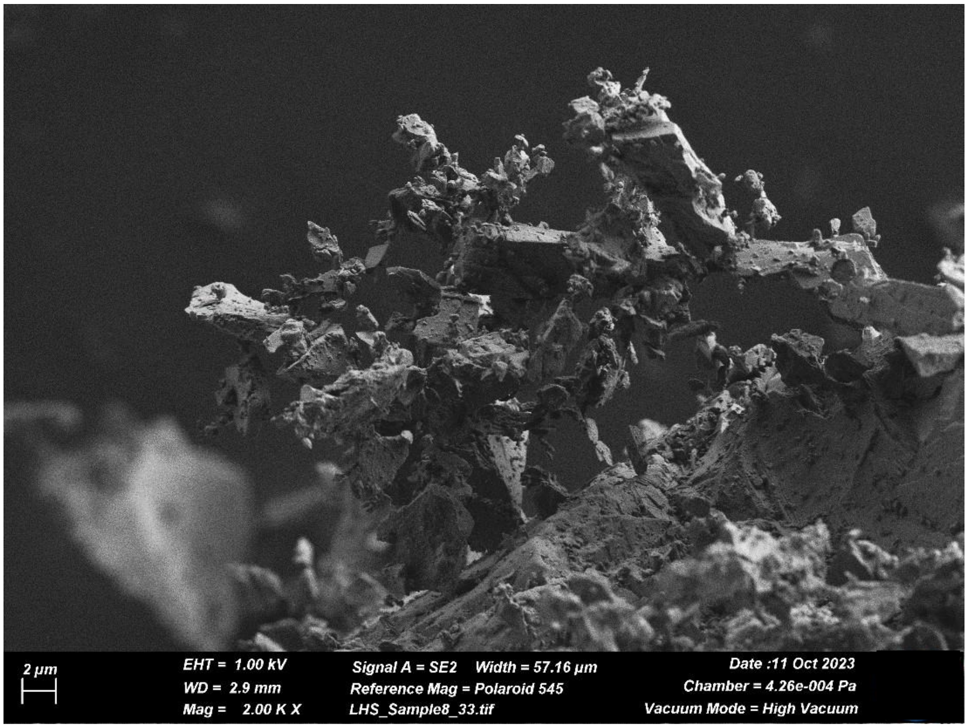


Fig. 8 SEM image at 2,000x magnification showing LHS-1D forming fairy castle structures at a loading of 0.672 mg/cm^2.

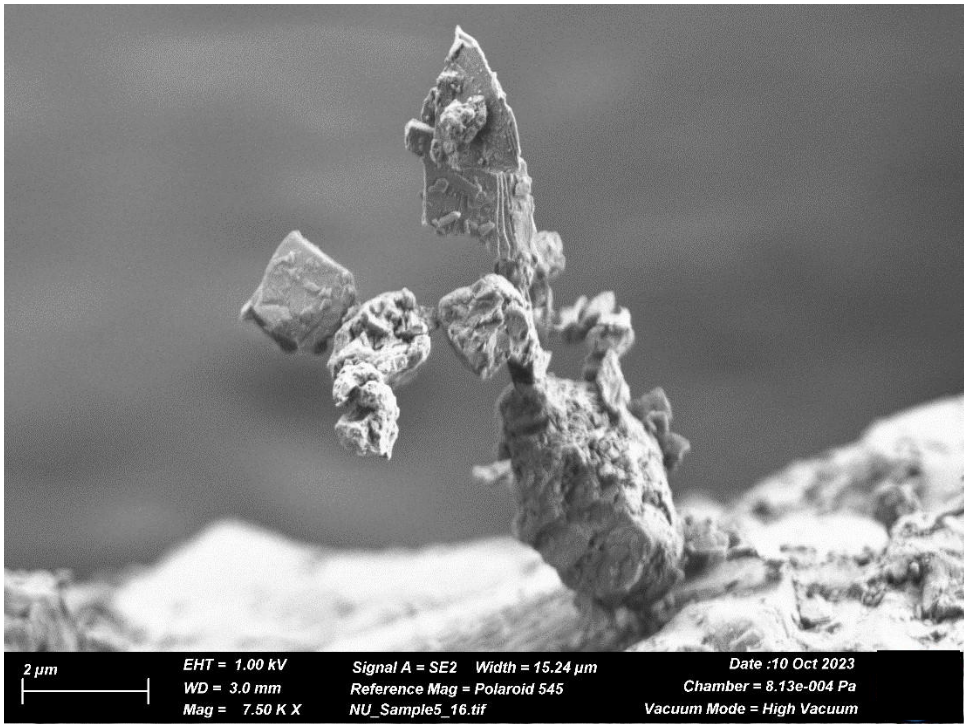


Fig. 9 SEM image at 7,500x magnification showing NU-LHT-4M forming fairy castle structures at a loading of 0.930 mg/cm^2.

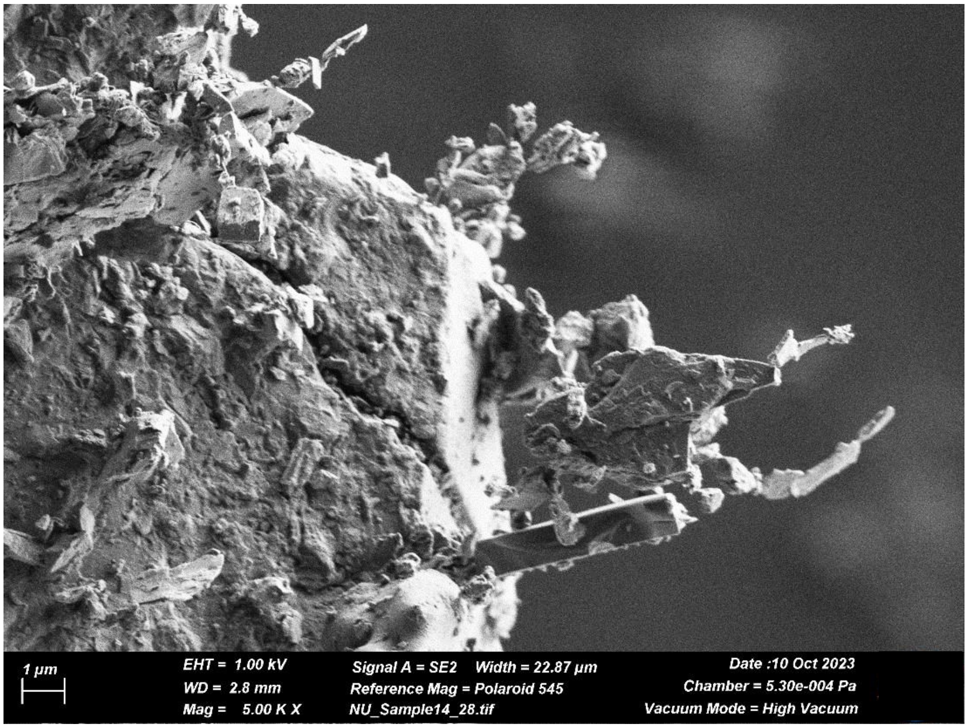


Fig. 10 SEM image at 5,000x magnification showing NU-LHT-4M forming fairy castle structures at a loading of 2.532 mg/cm^2.

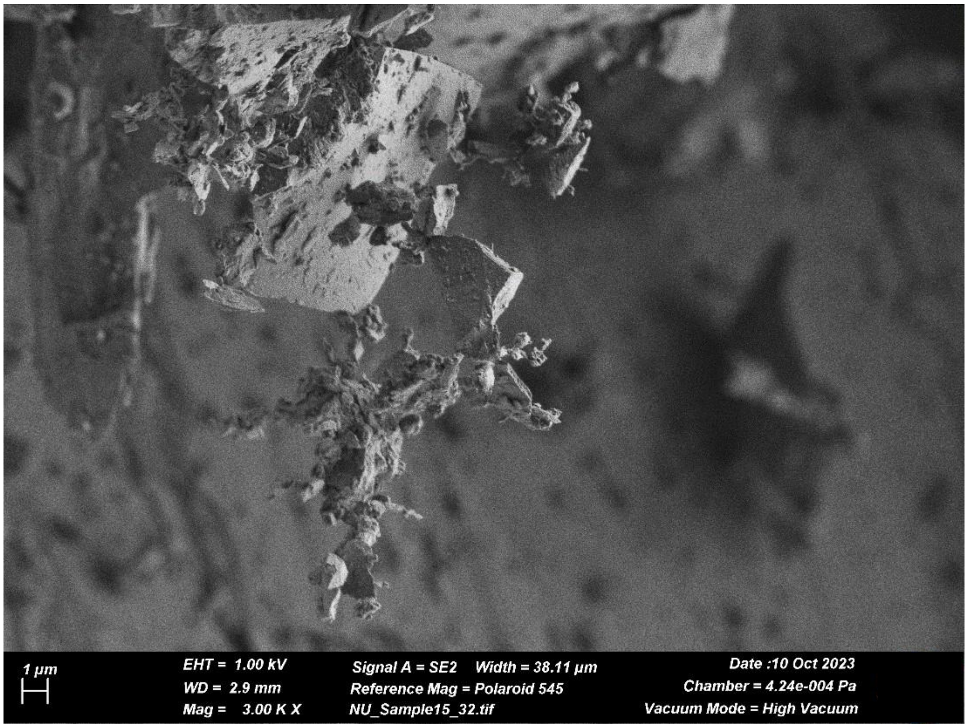


Fig. 11 SEM image at 3,000x magnification showing NU-LHT-4M forming fairy castle structures at a loading of 2.454 mg/cm^2.

IV. Conclusion

Percent area coverage relative to lunar regolith/dust is a difficult value to define as well as to calculate, as other researchers have also stated [3]. The techniques pursued in this research used digital image processing. It was determined from the data obtained that the microscope slide samples produced more consistent values for PAC than SEM stubs, even when analyzed independently by JSC and TAMU. While there still was variation in the calculations using the microscope slide data, the general trend of PAC with increasing dust loading (in mg/cm^2) was consistent between JSC and TAMU. In addition, both approaches recognized a difference based on the dust simulant used. However, the TAMU data suggested that LHS dust will exhibit a higher PAC at a given loading than the NU-type dust would; conversely the JSC data suggested that NU dust will exhibit a higher PAC at a given loading than the LHS-type dust. With the limited data available, it is inconclusive as to which PAC determination method is more accurate. The offset in the data is likely related to the method used to select the threshold for image analyses. Overall digital imaging does show promise as a method to determine PAC, but more experimentation is recommended to refine the technique(s). Applying the Michaelis-Menten equation form as a curve fit appears to model the shape of the data well, but the spread in the datapoints resulted in R^2 values in the 0.75 range, on average. Other curve fit models, such as the Hollings Type 2 functional response, will also be studied to assess their potential for fitting the data better than a Michaelis-Menten fit. Curve fitting the data presented in this paper, and the data that will be obtained in future research, is a meticulous process, and the best fit model is subject to change as more information and data are gathered.

Some of the difficulties associated with determining PAC via image analysis arise from the formation of fairy castle structures. These complex formations result in voids, channels, and bridges between dust particles. At low dust loadings, the particles and associated structures are unnoticeable to the eye or a camera without specialized imaging (for particle sizes of <40 micrometers), even if dust is present. Alternatively, a surface might look completely covered at a top-down glance, but shifting the viewpoint, lighting, etc. could show areas of the surface that are not in direct contact with the dust. This is a consideration for defining what is meant by PAC, because "this proposes a two-dimensional parameter for a three-dimensional phenomenon, even if it is on the micrometer scale."[1] It was originally assumed that dust "density" could be expressed as the mass of dust per surface area since the thickness of the dust on the surface was negligible relative to the length and width of that surface. In an ideal world, dust density could be quantified three-dimensionally such that the thickness of dust is not ignored, and the complex structures from fairy castling are accounted for. These measurements are not yet realized, but would be helpful to not only answer the question of "exactly how much of a surface is covered with dust?" but also "how might this be affecting other key physical parameters (e.g., optical properties, heat transport)?"

Perhaps the most significant finding from the current work was that even at very low dust loadings ($<0.5\ mg/cm^2$), the derived dust PAC increased significantly with two different types of simulants considered representative of the Moon's surface. The dust buildup may also be difficult to see with the naked eye or camera systems. A surface or system on a spacecraft that looks clean may still have enough dust on it to cause impacts, such as with heat rejection to the space environment. The early research described in this paper suggests additional study of dust deposition and accumulation, as well as the formation of fairy castle structures, is essential for continued lunar exploration.

Acknowledgments

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[1] This quote is from co-author Dr. K. M. Hurlbert who is a Principal Investigator for related research on heat transport affects from lunar dust on surfaces. Questions relative to this statement can be directed to katy.m.hurlbert@nasa.gov.