Comparing the Effects of Mineralogy and Particle Size Distribution on the Angle of Repose for Lunar Regolith Simulants. P. Easter[1*], J. Long-Fox[1], Z. Landsman[1], A. Metke[1], and D. Britt[1] [1]Department of Physics and the Exolith lab, University of Central Florida, Orlando, Florida 32816, USA. [*]peaster@knights.ucf.edu

Introduction: The physical properties of Lunar regolith vary across the Lunar surface, resulting in differing geotechnical properties at different sites. These differing physical properties are suspected to arise, in part, from variation in mineralogy between and within the two main Lunar geologic provinces, namely the Lunar highlands and the Lunar mare. Particle size is another key parameter that influences the mechanical behavior of the regolith, yet there is a knowledge gap in quantifying these sensitivities to particle size and composition. The angle of repose, a quality that represents the angle at which a material's slope can rest without failure [1], is of utmost importance for Lunar *in situ* resource utilization (ISRU) and exploration, as it impacts storage requirements, bulk material processing, and surface mobility. A higher angle is the result of a more cohesive material and is often associated with a higher internal friction. The CLASS Exolith Lab at The University of Central Florida produces Lunar regolith simulants which approximate the mineralogy of the Lunar highlands (LHS-1) [2] and mare (LMS-1) [3]. In addition to mineralogy, the simulants mimic a typical particle size distribution for Lunar regolith. The Exolith Lab also produces a very fine-grained version of both simulants to mimic the particle size of Lunar dust (LHS-1D and LMS-1D) [4][5]. This study examines the angle of repose of high mineralogical fidelity Lunar highlands and mare regolith simulants LHS-1 and LMS-1, respectively, as well as fine-grained ("Dust") versions of these simulants.

Methods: To study the effects of minerology and particle size on the angle of repose of Lunar simulants, both the standard and dust simulants were utilized**.** The particle size of LHS-1 and LMS-1 simulants range from 0.04 µm to 1000 µm with a mean of 85 microns and 110 microns respectively, whereas the LHS-1D and LMS-1D simulants are all less than 30 µm. 500 grams of each simulant was allowed to flow out of a funnel, down a chute and against a wall, then free fall to form a half cone at the base of the wall. This procedure is based on the Angle of Repose method by Geldart et al. [6]. Both the funnel and the chute had vibration motors attached to assure consistent flow of simulant onto the chute as well as ensure smooth travel down the chute. As the simulant accumulates in the half cone pile at the base of the wall, it forms a slope that builds to the angle of repose, undergoes slope failure, and repeats this process until all 500 grams of simulant is in the pile. The angle of the slope was measured before and after slope failure twice for each of the five trials using a GoPro and ImageJ processing software [7]

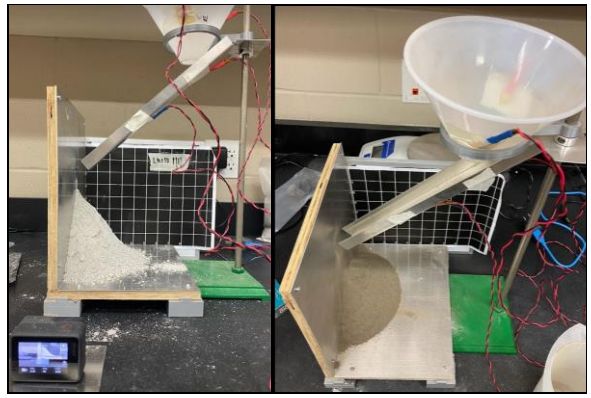

Figure 1. *Angle of Repose Experiment Setup*

Results: The pre- and post-failure angle measurements for LHS-1, LHS-1D, LMS-1, and LMS-1D are given in Table 1. As the regolith fell, there would be two to five failures before the slope stabilized. After most of the simulant had fallen into the pile, the angle became more consistent and the slope no longer failed. This is due to less disturbance from the lower volumetric flow rate of simulant into the pile at the end of the experiment, resulting in the final angle of repose given in Table 2. The analysis of slope angles before and after failure show that the Dust variants consistently had a steeper slope than their standard simulant counterparts. In addition, LHS-1 has a higher angle of repose than LMS-1. It is important to note that there was no noticeable trend in the magnitude of failure that the slope experienced, with failure ranging anywhere from 3° to 18°. Future work will aim to quantify the differences in the intensity and frequency of these failure events.

Table 1. Pre- and post-failure slope angles and their respective 1σ uncertainties.

Simulant	Pre-Failure Slope	Post- Failure Angle
LHS-1	41.21° ± 3.94°	30.86° ± 4.84°
LHS-1D	46.81° ± 1.82°	38.39° ± 0.99°
LMS-1	35.69° ± 1.65°	28.02° ± 3.04°
LMS-1D	47.52° ± 1.74°	38.13° ± 3.27°

Table 2. Average final angle of repose for each simulant along with the respective 1σ uncertainties.

Simulant	Average Final Angle
LHS-1	39.58° ± 1.14°
LMS-1	36.9° ± 1.12°
LHS-1D	46.36° ± 0.46°
LMS-1D	46.54° ± 0.82°

Discussion: There are multiple factors that can affect the angle of repose of a granular material. This experiment focused on mineralogical variation and particle size differences between each simulant. We conclude from the increased angle of repose of the Dust variants that particle size effects dominate the angle of repose of Exolith Lab Lunar regolith simulants. The small particle sizes of LHS-1D and LMS-1D are expected to result in a material with higher cohesion, increasing the angle of repose noticeably from the corresponding simulant with standard particle size range. While both composition and particle geometry impact the angle of repose, a quantitative comparison of the contributions of mineralogical effects and those of the particle geometry is yet to be completed, as knowledge of sensitivity to these covarying parameters is crucial to understand the mechanical behavior of Lunar regolith for ISRU and exploration purposes. However, it is noted that the slope-forming behavior of both LHS-1D and LMS-1D are dominated by particle size and do not seem to have strong mineralogically-driven differences.

The magnitude of observed slope failure did not appear to be determined by either particle size or mineralogy of the material. While the angle both before and after failure maintained their relative magnitude, with Dust simulants being highest and LMS-1 being the lowest, all of the simulants failed at a non-determinable rate. It was also found that the half cone piles of LHS-1D and LMS-1D had two different slopes. A steep angle was observed at the top of the slope where the grain size of the simulant was consistent and small, but due to atmospheric conditions, these extremely fine grains clump into large pieces (artificially increasing particle size) and these would roll down the slope, causing a relatively less steep slope towards the bottom of the pile (Figure 2). As we can see in both this experiment and experiments investigating the shear strength of LHS-1D and LMS-1D [8], the Dust simulants can behave in an counterintuitive manner due to their tendency to clump. Since this phenomenon is caused by testing in ambient atmospheric conditions, we took the measurement of the top half of the slope. It is also important to note that the slope forming and failure mechanisms of this material are expected to be different in Lunar surface conditions and this is a future direction for these experiments.

As the simulant slopes stopped failing and built to their final size, they approached the average pre-failure angle that was determined in Table 1. This is an important finding as it indicates that in the absence of extensive disturbance from simulant falling onto the pile, the resting angle of the pile is near the average pre-failure angle. While the pre-failure angles for the simulant had high variability, the average final angle was significantly more consistent in its angle and structure. These average final angles are what we consider the angle of repose of each simulant, as they are the steepest, consistent angle which the simulant slope forms.

In finding the angles of repose of mineralogically-accurate Lunar regolith simulants, we gain a better understanding of Lunar regolith and its properties. Understanding the angle of repose also allows us to better characterize simulant and tailor it better for various uses, such as rover test beds or plant growth studies.

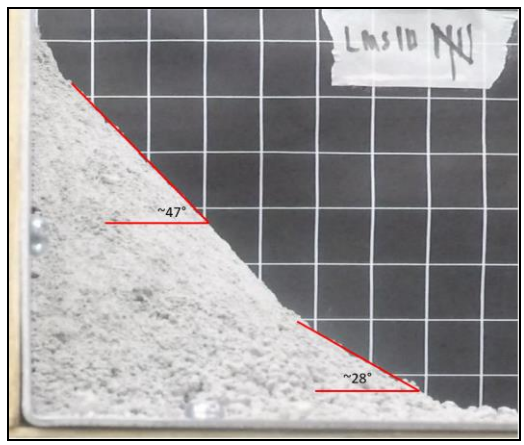

Figure 2. *LMS-1D Angle of Repose*

References:

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