New Insights into the Physical Properties of Regolith. B. Dotson, H. Sargeant, C. Millwater, P. Easter, D. Sanchez Valencia, J. Long-Fox, D. Britt, and P. Metzger, University of Central Florida, Department of Physics, 4000 Central Florida Boulevard, Orlando, FL 32816; email: bdotson@knights.ucf.edu

Introduction: With astronauts returning to the Moon under NASA's Artemis program, understanding the physical properties of lunar regolith will be important for the construction of landing pads, surface structures, or requisite infrastructure using *in situ resource utilization* (ISRU). Moreover, as missions strive to land larger and heavy spacecraft on the Moon, understanding the fundamental principles associated with material strength and cohesiveness of lunar regolith will be crucial for mitigating the effects of plume-surface interactions (PSI) from rocket exhaust.

Shear strength, a material property that represents the pre-failure, resistive force (per unit area) to a shearing load through constituent particle interactions is critical for PSI, ISRU, and lunar construction. Shear strength of a material is dependent on the applied normal load and is related to a material's cohesion, as described by the Mohr-Coulomb failure criterion [1]. Cohesion (C), also a material property, is a measure of the force that holds particles together. Understanding the relationship of shear strength and cohesion with other physical properties such as bulk density, particle size, and water content is relevant for both lunar and terrestrial applications, including experiments with simulated regolith [1].

This study examines the effects of density and particle size distribution on the shear strength and cohesion of lunar simulants using direct shear tests. For experiments involving lunar simulants on Earth, preliminary results highlighting the effects of atmospheric water on shear strength and cohesion are also discussed.

Methods: Direct shear tests were conducted using lunar highlands simulant (LHS-1) and lunar mare simulant (LMS-1) from the Exolith Lab, in accordance with ASTM D3080 [2,3]. Direct shear tests were also conducted using smaller-grained, dust samples of these simulants (known as LHS-1D and LMS-1D) as well as LHS-1 with 25% anorthosite agglutinates (LHS-1-25A) [4,5,6]. Shear tests with 1 mm and 44-80 µm glass beads were also examined as a control. All samples were exposed to atmosphere during testing, and "dry" samples were tested and weighed after baking for 24 hours at 140ºC.

Normal loads between 0.1-0.7 N were used, with roughly 20 shear measurements per target density for each sample. The sample density was adjusted using a vibration table between 20-40 Hz with <0.7 N normal load compaction. Direct shear strength measurements were obtained using a linearly actuated force gauge, noting the maximum force prior to material failure.

The cumulative and incremental particle size distributions for all samples were measured using a Cilas-1190 laser-diffraction size analyzer. Using the incremental particle size distribution, Full Width at Half Maximum ($FWHM_{PSD}$) was obtained for each sample using a 3-5 term, Gaussian fit in Matlab. As a new technique for geotechnical measurements, 3-D surface fits of shear strength data were calculated using quadratic Lowess regressions in Matlab with a weighted

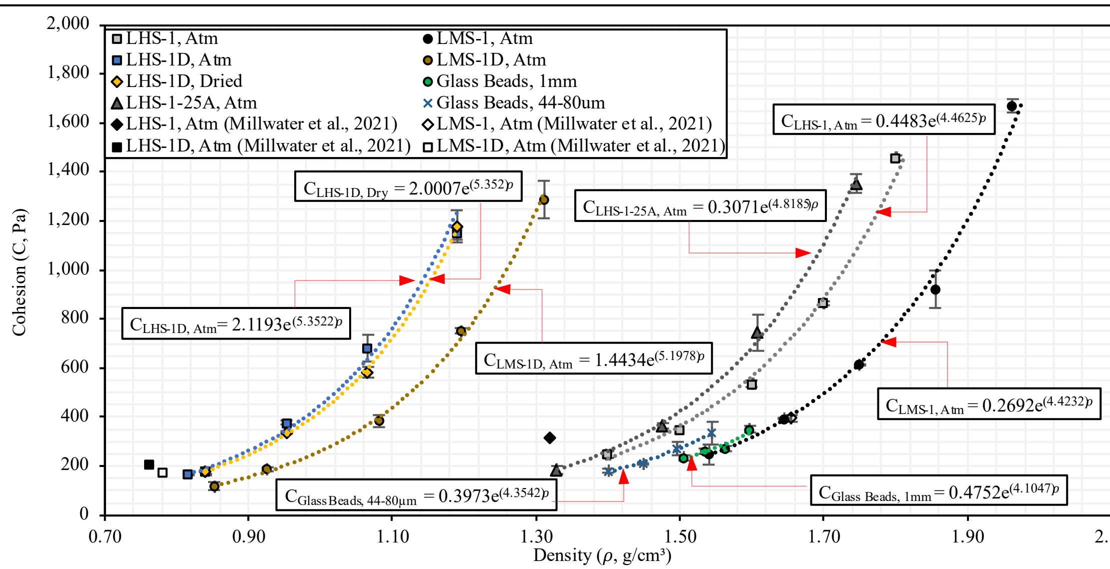

Figure 1. Exponential growth of cohesion with density as observed in lunar regolith simulants and glass beads.

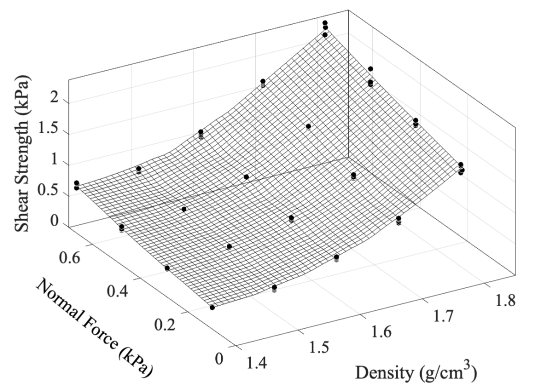

Figure 2. Shear Strength Versus Density for LHS-1.

span of 35-45%. These surface fit models were used to calculate shear strength and cohesion as a function of sample density and can be directly compared between samples to show the effects of atmospheric water, as discussed below.

Results: Cohesion as a function of density is shown in Figure 1, for each of the samples considered. Cohesion measurements by Millwater et al. (2022) are also shown in Figure 1, with similar results [1]. For each sample, cohesion increases exponentially with sample density. An exponential fit as a function of density, shown in Equation 1 below, was applied to this data in order to calculate the density growth constant (k) and initial constant (a) for each sample.

$$C(\rho) = a\, e^{k(\rho)} \quad (1)$$

Shear strength as a function of normal force and density is shown in Figure 2 for LHS-1. For each sample, an increase in sample density and normal force corresponds to an increase in shear strength.

Discussion: The results of this study demonstrate that density, particle size distribution, and water content can affect a sample's cohesion and shear strength.

Effects of density on shear strength and cohesion. A single, constant value for shear strength and cohesion is not appropriate when measuring or modeling PSI and ISRU applications, as an increase in density causes an exponential increase for both material parameters. When building landing pads or structures on the Moon, compaction of regolith will greatly increase the strength and cohesiveness of the surface material.

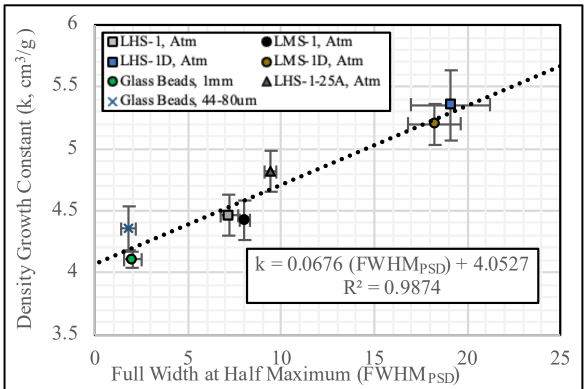

Figure 3. Density Growth Constant (k) vs. Full Width Half Max (FWHM) of particle distributions.

Effects of particle size distribution. As shown in Figure 3, an increase in $FWHM_{PSD}$ (meaning an increase in non-uniformity of particle size) corresponds to an increase in the rate of exponential growth of cohesion as a function of density. As shown in Figure 1, a smaller range of density is achievable with glass beads (near-homogeneous, spherical particles) compared to non-uniform samples. When building on the Moon, a more-diverse mix of particle sizes will result in larger density effects on regolith cohesion.

Effects of atmospheric water. Atmospheric water causes non-uniform changes in shear strength, based on sample density and normal load (Figure 4). For mid-range densities, only ~0.4% water absorbed can increase shear strength by roughly 15%. However, for lower densities with high normal loads, the same amount of absorbed water can cause a 5% decrease in shear strength. While additional investigations are needed, this highlights the importance of atmospheric water and humidity when considering regolith properties on Earth.

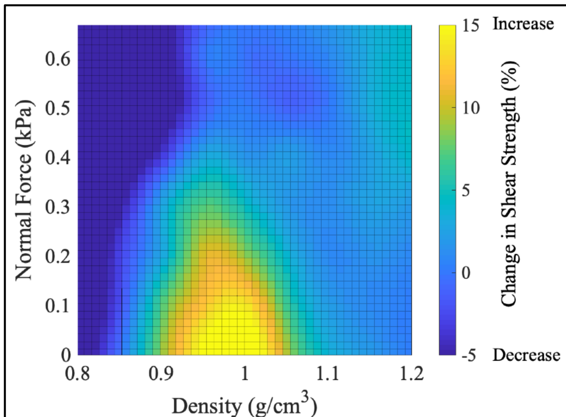

Figure 4. Humidity effects on shear strength for LHS-1D.

Conclusions: The physical and geotechnical properties of regolith can vary greatly based on density, particle size distribution, and absorption of atmospheric water; these parameters should be considered during any PSI or LRSU applications. Future studies should examine these effects under vacuum conditions, as well as the effects of particle shape on geotechnical properties..

References: [1] Millwater, C. et al. (2021), LPSC 53, 2038. [2] Exolith Lab, LHS-1 Spec Sheet (Jul. 2022). [3] Exolith Lab, LMS-1 Spec Sheet (Jul. 2022). [4] Exolith Lab, LHS-1D Spec Sheet (Jul. 2022). [5] Exolith Lab, LMS-1D Spec Sheet (Jul. 2022). [6] Exolith Lab, LHS-1-25A Spec Sheet (Feb. 2022).