Direct Shear Measurements of Lunar Regolith Simulants LHS-1, LHS-1D, LMS-1, and LMS-1D

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Introduction: Lunar exploration, infrastructure design, and Lunar development rely on an understanding of interparticle interactions of the regolith on the surface. Shear strength, a measure of material strength that is caused by opposing forces when one part of a body is pushed in a specific direction, and another part of the body pushes back in the opposite direction, resisting the force. Quantification of shear strength, and its Mohr-Coulomb parameters of cohesion (c) and angle of internal friction (ϕ), is vital to understanding the material strength to build any structures on the Moon including those developed with *in situ* resource utilization (ISRU). This experiment studies the shear strength caused by interparticle interactions through the direct shear test (ASTM D3080) in Exolith Lab lunar highlands simulant (LHS-1) and lunar mare simulant (LMS-1), as well as their pure dust (<30 µm) counterparts LHS-1D and LMS-1D.

Methods: LHS-1 stands for Lunar Highlands Simulant, simulating regolith mineralogy found on the lunar highlands. Particle sizes of LHS-1 range between <0.4µm to 400µm, and the mean particle size is 94µm. LHS-1D has the same mineralogy as LHS-1, but is ball milled for 24-48 hours producing a particle size of <30µm with a mean particle size of 7µm. For LMS-1, Lunar Mare Simulant of the lunar mare regolith mineralogy, particle sizes of this simulant range between <0.4µm to 300µm, and the mean particle size is 63µm. LMS-1D is also ball milled for 24-48 hours, producing a particle size of <30µm with a mean particle size of 7µm [2]. A breakdown of the minerology is detailed in the tables 1 and 2 below:

Table 1. Composition of LHS-1 and LHS-1D.

Component	% Composition
Anorthosite	74.4
Glass-Rich Basalt	24.7
Ilmenite	0.4
Olivine	0.3
Pyroxene	0.2

Table 2. Composition of LMS-1 and LMS-1D.

Component	% Composition
Pyroxene	32.8
Glass-Rich Basalt	32
Anorthosite	19.8
Olivine	11.1
Ilmenite	4.3

The experimental hardware consists of a force sensor, set on an Arduino-controlled linear actuator to move forward and backwards at a constant speed. Attached to the front of the linear actuator is a box, with a split in the middle designed to slide, pushed by the force sensor, along the tracks on the box that ensure shearing parallel to the direction of motion.

The known mass of simulant was placed into the direct shear box and was then gently agitated, so it remained light and fluffy. The simulant was only packed as much as was caused by the downward, normal force of weights placed on top of the simulant in the box. The weights, stacked incrementally to increase normal load placed on top evenly distributed force across the box. The resultant normal loads in the experiment were 0.098, 0.193, 0.288, 0.383, 0.478, 0.573, and 0.668 kPa. The shear force for each of the 5 trials at each of the 7 normal loads (measured in Newtons on the force gauge) is recorded at the maximum force the sensor reads. This is taken to be the force applied right before failure, and this shear force is converted to shear strength based on the area of simulant being sheared. The cohesion and angle of internal friction are estimated through a linear regression on the direct shear data, based on the Mohr-Coulomb model of shear strength. Uncompressed bulk density (ρ_b) is also calculated using the known mass of simulant required to completely fill the volume direct shear box.

Results: As shown in Figures 2 and 3, Shear stress at failure in direct shear increases linearly for both the standard and dust only LHS-1 and LMS-1. Table 3 gives the estimated Mohr-Coulomb parameters of cohesion and angle of internal friction, as well as uncompressed bulk density.

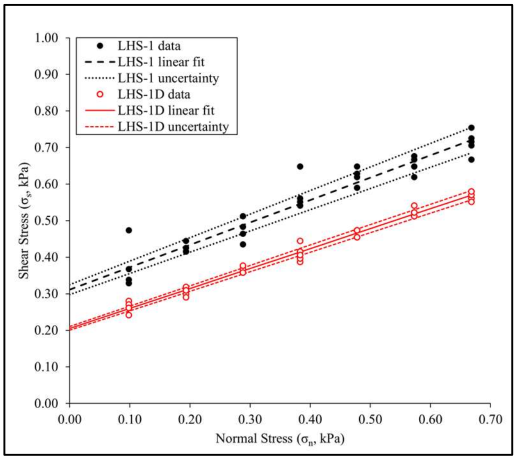

Figure 1. Results of direct shear testing of LHS-1 and LHS-1D.

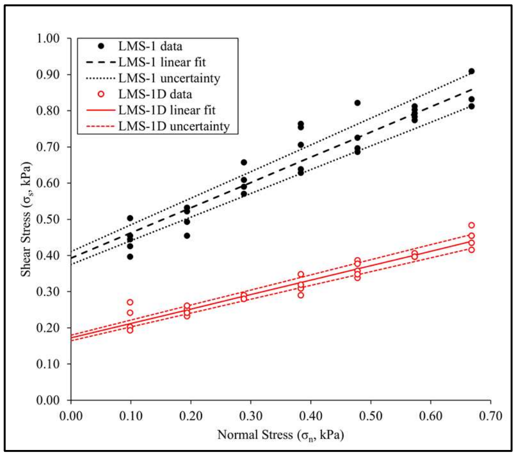

Figure 2. Results of direct shear testing of LMS-1 and LMS-1D.

Table 3. Cohesion (*c*), angle of internal friction (ϕ), and bulk density (ρ_b) of LHS-1, LHS-1D, LMS-1, and LMS-1D estimated from data collected through direct shear testing.

	c (kPa)	ϕ (°)	ρ_b (kg/m^3)
LHS-1	0.311±0.013	31.49±1.82	1320.77±3.73
LHS-1D	0.205±0.005	28.62±0.67	762.44±4.95
LMS-1	0.393±0.018	34.84±2.37	1654.98±10.45
LMS-1D	0.172±0.007	21.77±1.01	781.49±6.34

Discussion: As shown in Figures 2 and 3, shear stress at failure in direct shear tests of LHS-1, LHS-1D, LMS-1, and LMS-1D followed the expected linear increase with applied normal stress. In addition, shear strength overall was higher in the regular simulants LHS-1 and LMS-1 compared to their dusty counterparts LHS-1D and LMS-1D). Bulk density was lower in the dusty simulants because the small particles in the dusty stimulants tend to clump together to form larger clumps held by static electricity and ambient moisture. These clumps were not broken up during shear testing, as the simulant was allowed to sit lightly in the container and remain fluffy rather than be mixed or packed after being loaded into the box, except for the compression from the normal load. As a whole: bulk density, cohesion, and the angle of internal friction decreased in the dusty simulants LHS-1D and LMS-1D as compared to their regular versions LHS-1 and LMS-1. A possible cause of this could be the lack of grain-to-grain contact in LHS-1D and LMS-1D, with the dusty simulants sticking together much more and forming clumps that act as one body, artificially increasing particle size, also seen in [1]. The higher angle of repose for LHS-1D and LMS-1D relative to LHS-1 and LMS-1, respectively, given in [1] indicates that the dust simulants have higher shear strength, but this is not seen in this study and is attributed to density differences in the respective standard and dust simulants. This is difference in density is caused by the increase in particle size due to clumping during direct shear testing. The impact of this will be mitigated in future work by mixing and packing the dusty simulants in the shear force box rather than gently scooping, to break up the clumped particles and allow for more interparticle interaction This packing will not only break up the clumps but serve to enable comparisons of the dusty and standard simulants at similar densities.

Conclusions: Future missions on the lunar surface depend on the understanding of the physical properties of the lunar regolith. Moreover, it is important to understand the differences between the geotechnical properties regolith itself and the dust present. Understanding the regolith and dust's shear strength, and their Mohr-Coulomb parameters of cohesion (*c*) and angle of internal friction (ϕ), is necessary to understanding the material strength to build structures on the Moon through *in situ* resource utilization (ISRU). This experiment provides more insight into the differences between the dusty and non-dusty versions of the simulated regolith. Future works building off this study might examine the differences packing density, as well as the effects of Earth's atmosphere/humidity on packing density, as done in Long-Fox et al. (2022) [6].

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References: [1] Exolith Lab (2021), LHS-1 Spec Sheet (Nov. 2021). [2] Exolith Lab (2021), LHS-1D Spec Sheet (Nov. 2021).[3] Exolith Lab (2021), LMS-1 Spec Sheet (Nov. 2021). [4] Exolith Lab (2021), LMS-1D Spec Sheet (Nov. 2021). [5] Easter, P. et al. (2022), 53rd Lunar and Planetary Science Conference Abstract. [6] Long-Fox et al. (2022), 18th Biennial ASCE Earth and Space Conference Proceeding, in review.