LUNAR SURFACE INNOVATION INITIATIVE: GEOTECHNICAL EVALUATION OF LUNAR REGOLITH SIMULANTS

A. C. Martin1, K. R. Stockstill-Cahill1, C. M. Wagoner1, R. N. Kovtun2, and J. E. Gruener2,1JHU Applied Physics Laboratory (11100 Johns Hopkins Rd., Laurel, MD 20723), 2NASA-JSC/Jacobs (2101 NASA Parkway, XI4-JETS, Houston, TX 77058)

**Introduction:** The plan to return humans to the Moon during the NASA Artemis program requires development of many different processes and technologies. A critical aspect of this development and maturation of technology is testing under relevant lunar surface conditions, including in the presence of and using lunar regolith simulants.

While simulants are approximations of lunar regolith, they do not reproduce all characteristics that lunar regolith exhibits. To ensure that we understand these differences between simulants and lunar regolith, extensive characterization needs to be done on simulants so we can validate testing lunar technologies. The NASA simulant team has partnered with the Lunar Surface Innovation Initiative (LSII) at JHU Applied Physics Laboratory (JHU-APL) to characterize and assess lunar simulants.

This report is complimentary to the reports presented in the 2020 [1] and 2021 [2] Lunar Simulant Assessments previously published by the JHU-APL LSII team. This 2022 update includes simulants that were previously assessed (Exolitoh Labs LHS-I and LMS-1; Off Planet Research OPRH3N and OPRL2N; Colorado School of Mines CSM-LHT-1 and CSM-LMT-1) and two other simulants (Deltion’s OB-1A and USGS/NASA NU-LHT-4M) not previously examined by our team. A full description of each company and their product is provided within the assessment.

This year’s assessment focused on geotechnical characteristics of the 8 simulants and how they compared to the lunar regolith returned by Apollo and other missions. Geotechnical properties are important for technology development in the areas of in situ (ISRU), mobility, dust mitigation, excavation and construction, hazards, and more. Understanding additional simulant characteristics are of interest to the community because some geotechnical properties, like relative density, were noted as some of the most important properties impacting Apollo program [3]

**Methods:** The JHU-APL LSII simulants team focused on 4 main types of geotechnical procedures for this assessment: particle size distribution, minimum and maximum density, specific gravity, and direct shear strength. The NASA Simulant Advisory Committee provided us with 7.5 kg of 7 of the 8 simulants and we purchased the other one.

**Particle Size Distribution:** The simulants were sieved into 6 different particle size fractions using sieves pans of varying mesh sizes (microns) from coarsest to finest: 500, 300, 150, 75, 45, pan. We emptied 500g of sample into the top sieve, ran the shaker machine for 20 minutes, and then weighed each sieve from which the mass of each sample within that size range was calculated.

**Minimum and Maximum Density:** We measured the density of uncompacted and compacted simulant to collect the minimum and maximum density measurements. For both measurements we used an aluminum cylinder to collect and record the weight of the sample. For minimum density, sample was poured into the cylinder using a funnel and tube. The tube was then lifted carefully in a circular motion to fill the cylinder with uncompacted simulant. For maximum density, the soil was lifted up compacted with a cylindrical weight to tightly compact the soil. For both measurements, the soil was leveled off and any extra material was brushed off before weighing.

**Specific Gravity:** Specific Gravity was measured using a 500 mL volumetric flask, funnel, thermometer, distilled water, and vacuum hose. Because this test measures the ratio of solid particles to the weight of water, each simulant had to be submerged into water. We weighed 75 g of simulant in the flask then added water. From here we applied a small vacuum to the flask until the trapped air bubbles disappeared. The filled flask was weighed again and the density was calculated.

**Direct Shear:** We used a GeoTac Digishear machine to collect our shear strength measurements of the simulant. Dry simulant was loaded into the sample holder and using Digishear software, a vertical load was 1st applied, followed by a horizontal load. We used 3 different vertical stress loads: 500, 1500, and 3000 pounds per square foot. Once the vertical load was stable, a 0.25 inch displacement was performed horizontally. The software collects the resulting strain data and plots it over a strain curve. The peak shear stress was determined for each confining stress and they were plotted against the corresponding stress. From these strain curves, we calculated the cohesion and friction angles for each simulant.

**Results:** To better understand our data results, we broke the simulants into two groups: lunar highlands and lunar mare. These two groups will be used to display the outcome from the 4 methods in the assessment. For the purpose of this abstract, lunar highland results are displayed.

**Particle Size Distribution:** Particle size distribution (PSD) curves were created and compared to the Apollo average PSD. In general, the simulations have a fairly good distribution all within one standard deviation of the Apollo PSD. All simulants displayed a steeper slope around the 45-150 um range than the Apollo data. The simulants, OB1A, OPRH2N, and
OPRL2N plot the closest to the Apollo average within the smallest particle size range.

**Minimum and Maximum Density:** All simulants except 2 (OPRH2N and OPRL2N) display minimum densities that exceed the range of minimum densities measured from returned lunar samples. On the contrary, all simulants plot within the range of maximum densities measured from returned lunar samples. This suggests that the simulants have a lower porosity when uncompacted than lunar regolith, which leads to less compressibility in the simulants. This should be considered when experimenting with compressing regolith materials.

**Specific Gravity:** All the highland and mare simulants fall within specific gravity ranges measured for lunar soils. The highest specific gravity measured for highland and mare simulants are, respectively, OB1A (3.1) and Exolith LMS-1 (3.1).

**Direct Shear:** All simulants revealed cohesion values greater than the range of cohesion measured for lunar regolith but they all fall within the range of friction angles (Fig. 4). The closest cohesion match between simulants and lunar regolith are NU-LHT-4M (8kPa) and OPRL2N (7kPa).

**Conclusion:** While the assessment looks at general characterizations and techniques, users should take caution when using simulants to their work to ensure the simulant with ideal properties is selected. While these simulants should meet the needs of most users, most providers are able to adapt their product for a specific user when appropriate.

**Acknowledgements:** We appreciate the Civil and System Engineering Department at the Johns Hopkins University for letting us use their Soil Mechanics Laboratory to conduct most of the tests presented in this report. A special thanks to Prof. Lucas de Melo for the taking the time to train the APL team and supervise the lab work.