JHU-APL LSII REPORT:

2022 Lunar Simulant Assessment

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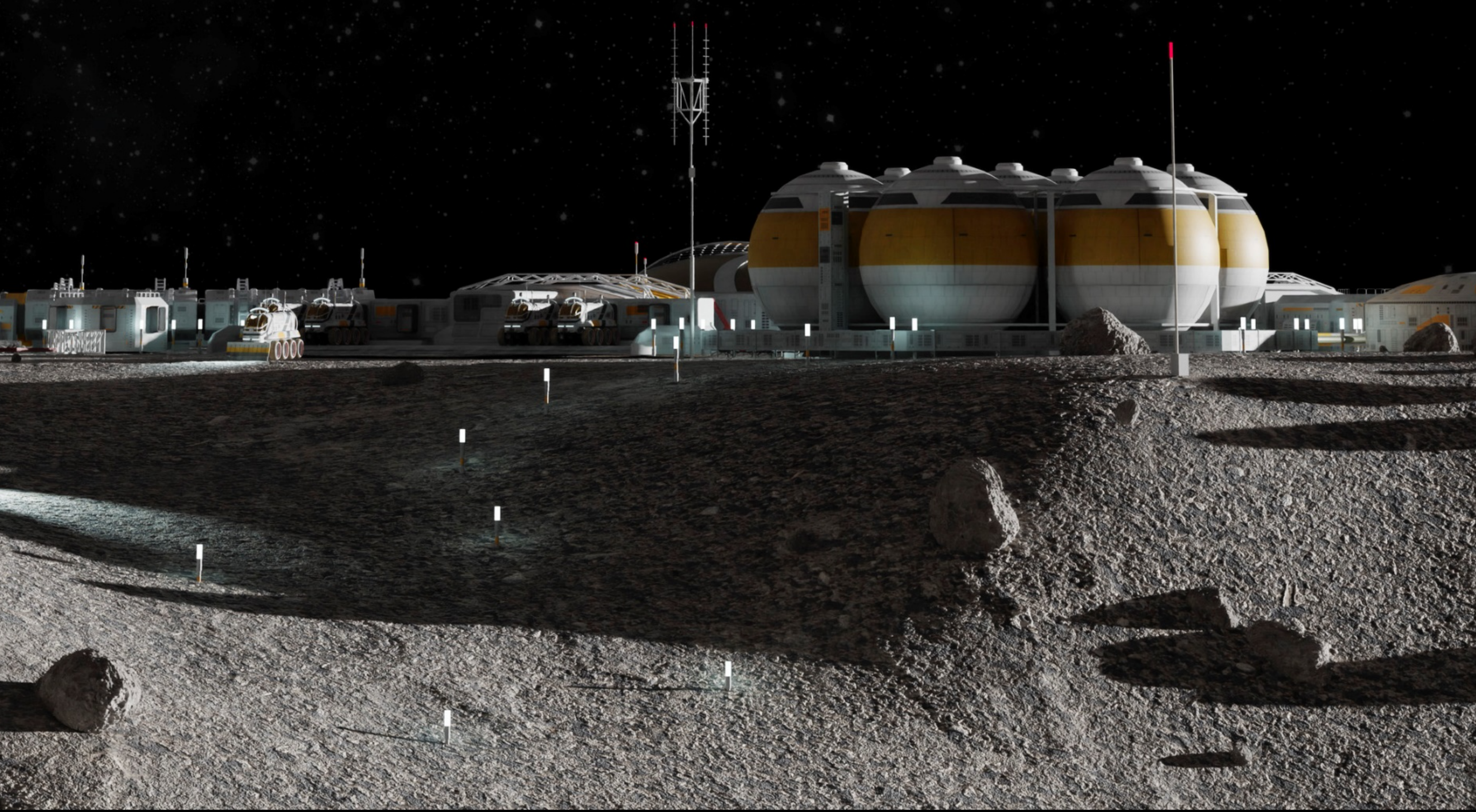

EXECUTIVE SUMMARY

This report presents a geotechnical assessment of eight lunar regolith simulants. Five of these are highland regolith simulants and three are mare regolith simulants. This report also provides complimentary data set to that presented in the 2020 and 2021 Lunar Simulant Assessments previously published by the JHU-APL LSII team. This 2022 update includes simulants that were previously assessed (Exolith Labs LHS-1 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.

This document provides information regarding each simulant provider, their available simulants, comparison of the evaluated simulant geotechnical characteristics to Apollo samples, and details regarding supply chain and quality control. The three commercial providers (Exolith, Off Planet Research, and Colorado School of Mines) provided updated information; the other two simulants are not currently in production by Deltion and USGS/NASA, so information is based on previous publications and personal communication with members of the NASA Simulant Advisory Committee. The simulant materials examined were provided by that committee from Johnson Space Center, which were available from their existing supplies. This included some simulant obtained from commercial providers using feedstocks that may differ from their current production feedstock, which is noted where applicable.

As detailed in this document, the geotechnical properties of many of the simulants tested are similar to those properties of returned lunar soils. The highland and mare simulants exhibit a particle size distribution within one standard deviation of an average Apollo regolith. Most of the simulants presented minimum densities lower than those encountered in returned lunar samples, but maximum densities were found to be similar to those measured for returned lunar samples. The difference between maximum and minimum densities was smaller for all simulants when compared with the difference encountered for returned lunar samples. All highland and mare simulants plot within the range of specific gravity values measured for returned lunar samples. Shear strength measurements produce friction angles that match those measured for returned lunar samples, but all cohesion values measured for the simulants exceed the range measured for lunar samples. For most applications, these differences from returned lunar regolith are not significant. However, we encourage all simulant users to carefully consider the implications for their specific application or experiment and to consult with a lunar geologist/scientist before ordering or using simulants.

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INTRODUCTION

Several groups have examined lunar regolith simulants to understand their resources and inherent limitations, for testing technologies for the lunar surface. In 2010, the Lunar Exploration Advisory Group (LEAG) and the Curation and Analysis Planning Team for Extraterrestrial Materials (CAPTEM) released a detailed report of their findings on the lunar regolith simulants available at that time (e.g., JSC-1, JSC-1A, NU-LHT), evaluating the strengths and weaknesses for various applications (Simulant Working Group, 2010). In addition, excellent summaries of the history and shortcomings of these simulants were presented by Taylor and colleagues (Taylor and Lie, 2010; Taylor *et al*., 2016). Since that time, new simulants have been developed by various groups in academia and private industry to address the limitations identified in previous simulants.

In 2020, the APL Lunar Surface Innovation Initiative (LSII) Team began evaluating the new generation of lunar simulants from these new providers, including CLASS Exolith Labs, Off Planet Research, and Outward Technologies. The assessment provided an initial evaluation of six lunar regolith simulants (LHS-1, LMS-1, OPRH3N, OPRL2N, 2020-LHA-1, 2020-LMA-1), and included new analyses of composition and particle shape and size and an evaluation of their potential suitability for specific uses (Denevi *et al.,* 2020). In 2021, the APL LSII Team updated this assessment to eight available lunar simulants (LHS-1, LMS-1, OPRH3N, OPRL2N, CSM-LHT1, CSM-LMT1, 2021-LHA-1, and 2021-LMA-1), six from the same providers, plus two from a new provider at the Colorado School of Mines. Previously-evaluated simulants had all undergone significant changes to their feedstock or production that could affect the assessment (Stockstill-Cahill *et al*., 2021). The 2021 assessment included analyses of the simulants' particle size-frequency distribution, particle morphology, and composition as well as an assessment of how suitable each simulant is for various applications (Stockstill-Cahill *et al*., 2021).

Summary of changes to the 2022 Assessment: In this year's assessment, we change our focus to the geotechnical characteristics of lunar regolith simulants and how these compare to lunar regolith returned by Apollo and other missions. Geotechnical properties are important for technology development in the areas of ISRU, mobility, dust mitigation, excavation and construction, hazards, and more. Carrier (2005) cited relative density as "the most important and interesting geotechnical property discovered during the Apollo program", so understanding additional simulant characteristics are of great interest to the community.

The geotechnical properties of the lunar soils returned by Apollo and Luna missions were studied extensively in the late 1960s and early 1970s (e.g., Scott and Roberson, 1969; Costes *et al*., 1970a; 1970b; Cremers *et al*, 1970; 1972; Cremers and Birkebak, 1971; Jaffe, 1971; Mitchell *et al.*, 1972; 1974; Gromov et al., 1972; Vinogradov, 1972; Carrier *et al*., 1973a, 1973b; Cremers and Hsia, 1973; Ivanov *et al*., 1973a; 1973b; Leonovich *et al*., 1974; 1975). These previous studies used a variety of ambient, nitrogen, and Mars-level vacuum environments as well as high vacuum environments for their measurements and we've attempted to note this when possible. This year, all measurements were done under ambient pressures and room temperature, so caution is taken when comparing our measurements to similar measurements completed on lunar regolith, especially those done *in situ* on the lunar surface. Undeniably, lunar regolith behaves differently on Earth, even under vacuum, due to differences in gravity. Carrier et al. (1991) noted that the combination of cohesion and frictional strength of lunar regolith, combined with the low lunar gravity, Apollo astronauts were able to dig trenches and drill core holes with vertical walls excavated to a depth of 3 meters. In fact, this regolith behavior on the lunar surface was exploited by later Apollo missions to deploy instruments beneath the lunar surface in open drill core holes. Carrier et al. (1991) also suggested that the presence of ice at the lunar poles (an unknown at the time) would interfere with the agglutination process and possibly create grains with less irregular surface, decreasing the regolith cohesion. In light of our increased understanding of polar ice deposits and our ability to create regolith-ice simulants, our community has the opportunity to test this hypothesis and better constrain the nature of lunar regolith at the lunar poles.

This works attempts to compare our lab geotechnical measurements of simulants to similar lab measurements done on lunar regolith. However, we also include geotechnical measurements of lunar regolith done *in situ* at the lunar surface in data tables in order to illustrate variations in geotechnical characteristics that may result at the lunar surface. The reader should note how those differences could impact their experimental work in the lab and how their technological approach might differ at the surface of the Moon.

This work presents measurements of the particle size distribution (PSD), minimum and maximum density, specific gravity, and shear strength in terms of soil cohesion and friction angle. (We also attempted to complete permeability tests, but the results were inconclusive because water failed to completely saturate the soils in 8 hours, probably due to the very fine particle size of the simulants.)

Particle size distribution is an important characteristic, as the lunar regolith samples spans a fairly narrow range of particle-size distributions (Carrier, 1973) and is characterized as a well-graded/poorly-sorted silty-sand to sandy-silt (Carrier et al., 1991). For a civil engineer, soils with large size particles are stronger due to the higher inter-particle friction, while finer soils are more sensitive to water content. If we know the particle size distribution of a soil, we can make predictions about its strength and properties.

Minimum and maximum density are important parameters for determining the relative density of a soil, which Carrier et al. (1991) cited as the most significant geotechnical property of lunar soils. Relative density can vary depending on how the soil particles are shaped and how closely they can pack. At the lunar surface, the in situ relative density range was 65% at the surface to 90% below 30 cm depth (Carrier et al, 1991). Therefore, it is important to know the minimum and maximum density of simulants (and in turn their relative density), and how these values compare to those measured for lunar regolith, when using simulants to test technology. These density values have important implications for any applications that involves excavation and compaction of regolith and surface stability on the Moon.

The specific gravity of soil is defined as the ratio of soil's mass to the mass of an equal volume of water at 4°C. The specific gravity of lunar soil is related to the relative proportions of different particle types (mineral and rock fragments breccias, glass, agglutinates) as well as the particles' porosities. These particle's porosities are in turn related to voids between the grains, on the exterior of grains, as well as enclosed voids in lunar particles. Specific gravity helps engineers understand how porous the soil is or how many voids it contains, as well as how saturated the soil is with water. This information can be used to predict whether the regolith will be stable enough to support a structure.

Lastly, measuring the shear strength of the regolith is used to determine the cohesion and angle of internal friction of regolith material. Soil cohesion is important to understanding the strength of the material to support structure, whereas the frictional angles reveals the stability condition of the material on slopes.

METHODOLOGY

We obtained eight lunar regolith simulants from five producers for our 2022 Lunar Simulants Assessment in collaboration with the NASA Simulant Advisory Committee. The NASA Simulant Advisory Committee provided us with 7.5 kg of seven of the eight simulants; Exolith Laboratories LHS-1 highland and LMS-1 mare simulants, Off Planet Research OPRL2N mare simulant, Colorado School of Mines CSM-LHT-1 highland and CSM-LMT-1 mare simulants, Deltion OB-1A highland simulant, and USGS NU-LHT-4M highland simulant. We purchased 7.5 kg of OPRH2N highland simulant from Off Planet Research for our analyses. The geotechnical measurements completed are detailed below.

Particle Size Distribution: Particle size distribution was measured using six 8-inch (203 mm) diameter ASTM E11 Test Sieves nested from coarsest to finest with a sieve pan at the bottom to catch the fines (Fig. 1 left). The sieve sizes were selected by mesh size to split grains into six standard particle size splits (Table 1). We emptied 500g of sample onto the top sieve, attached a lid, and put it on the sieve shaker machine (Fig. 1 right). We ran the shaker machine for each sample for 20 minutes. Each sieve was then weighed and the mass of the sample within that size range was calculated. We noticed that for both mare and highland simulants, the larger particles were darker than the finer particles (Fig. 1 left).

Table 1: Mesh size and particle sizes separated by sieves used for this work.

ASTM E11 Opening Size	Particle size (microns)
35	>500
50	297-500
100	149-297
200	74-149
325	45-74
pan	<45

Figure 1: Sieve pans containing sieved simulant (left) and sieve shaker machine (right).

Minimum and Maximum Density: For the minimum and maximum density measurements, we measured the density of uncompacted and compacted regolith simulant. Minimum density was measured using an aluminum cylinder with a volume of 943.9 cm^3. The weight of the empty cylinder was recorded, then a tube was placed into the cylinder base and the sample was poured in using the funnel at the top of the tube (Fig. 2 left). When enough simulant to fill the cylinder was in the tube, the tube was carefully lifted while moving in a circular motion until the cylinder is filled with uncompacted simulant. Next, the top of the simulant was leveled off to remove excess simulants and any extra material is brushed off outside of the cylinder (Fig. 2 middle). The cylinder with soil was weighed and the cylinder mass was subtracted to determine the mass of material within the cylinder.

Maximum density was measured in the same cylinder with compacted soil. First, the soil was scooped into the cylinder until overflowing. A cylindrical weight was placed on top of the soil and force was manually applied to push the soil tightly into the cylinder (Fig. 2 right). Once soil compaction was complete, the top is leveled off and any extra material was brushed off the outside of the cylinder. The cylinder with soil was then weighed and the cylinder mass was subtracted to determine the mass of material within the cylinder.

Figure 2: Lab set up used for measuring minimum and maximum density. (Left) Tube placed inside cylinder to pour regolith materials into cylinder. (Middle) Excess material being brushed off cylinder before measuring the final weight. (Right) Cylindrical weight being used to compact material into cylinder for maximum density measurements.

Specific Gravity: Specific gravity was measured using a 500 mL volumetric flask, funnel, thermometer, distilled water, and vacuum hose (Fig. 3 left). This test measured the ratio of solid particles' unit weight to the unit weight of water as $G_s = M_s / M_w$, where M is the mass of soil and water. We recorded the mass of the clean, empty volumetric flask (M_1) and the flask filled with water (M_2). Then ~75 g of soil was added to the flask and weighed (M_3) and distilled water was added to the flask until it was ~2/3 full (Fig. 3 middle). Using a vacuum pump attached to the top of the flask, a vacuum was slowly applied to removed trapped air while swirling the flask for ~10 minutes until the bubbles disappeared. With the vacuum pump removed, water was carefully added to fill the flask up to the 500 mL mark and the flask was weighed again (M_4) (Fig. 3 right). The temperature of the water (20°C) was taken before soil was added to each test to ensure tests were conducted at the reference temperature (T=20°C so that the density of water is 998.23 kg/m^3). From these measurements, the density of the soil was calculated by:

$$G_S = \frac{(M_3 - M_1)}{(M_2 - M_1) - (M_4 - M_3)}$$

Figure 3: Lab set up used for Specific Gravity. (Left) The 500 mL volumetric flask, vacuum tub hose, thermometer, funnel, and scale used to conduct the experiment. (Middle) Simulant material combined with the water. (Right) Sample being weighed at the end of testing.

Direct Shear: Direct shear was measured using a GeoTac Digishear machine that applies a horizontal and vertical load to determine the shear strength of soil materials. All measurements for this work were done under ambient conditions. Dry regolith simulant was loaded into two equally-sized, stacking-ring sample holders, ensuring the sample filled past the adjoining ring surface (Fig. 4 left). The sample holder was placed in the machine with a ball joint added on top (Fig. 4 middle). Using Digishear software to control the machine, a confining stress was applied vertically to the soil (Fig. 4 right). We used 3 different confining stresses for each sample, 500 pounds per square foot (PSF), 1500 PSF, and 3000 PSF. Once the vertical stress was stable, a horizontal stress was applied to the upper ring. This pushes the top half of the sample holder while the bottom half stays in place. The machine is moving 0.1 inches per minute to a maximum displacement of 0.25 inches. The software collects the resulting strain data and plots it on a stress-strain curve (displacement in inches vs. shear force in lbs) for each confining stress. The peak shear stress was determined for each confining stress and these three values were plotted against the corresponding confining stress on the x-axis. We then plotted a trendline through these three data points and determined the equation of that line, where the y-intercept gives the cohesion of the soil and the slope of the line is the arctangent of the friction angle. In this report, we provide the cohesion and friction angles for the simulants studied.

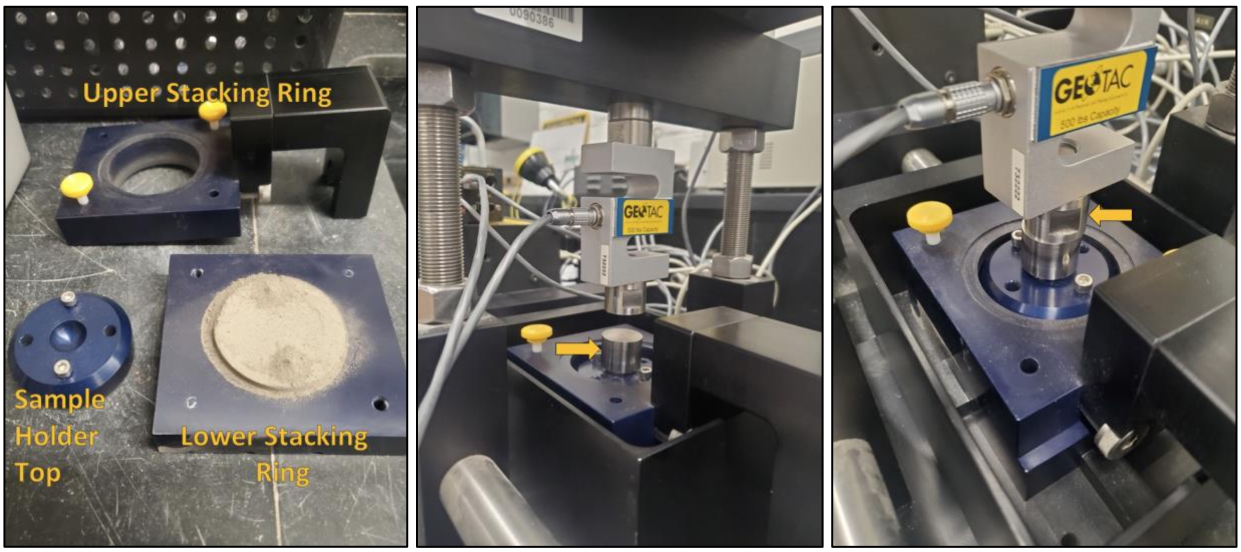

Figure 4: Lab set up used for Shear Strength Measurements. **(Left)** A simulant sample in the lower stacking ring (post-test), with the upper stacking ring in the background and sample holder top to the left. **(Middle)** Sample holder placed in machine with ball joint on top (yellow arrow), prior to confining stress being applied. **(Right)** Sample holder with confining stress being applied (yellow arrow) during test.

SIMULANT PROVIDER: THE EXOLITH LAB

Company Background

The Exolith Lab (formerly called the CLASS Exolith Lab) is a not-for-profit extension of the Center for Lunar and Asteroid Surface Science (CLASS), a NASA-funded SSERVI node at the University of Central Florida. Exolith Lab was started in 2014 as part of the Small Business Innovation Research (SBIR) program with Deep Space Industries. The University of Central Florida CLASS took over the equipment and facility in 2018 and formed the Exolith Lab. Initially, their work focused on the production of asteroid simulants, but has expanded to include a variety of lunar and martian simulants as well. As part of the current CLASS SSERVI node, Exolith is funded for the next three years. Dr. Daniel Britt is the director of CLASS and brings a wealth of experience understanding the physical properties and mineralogy of asteroids, comets, Moon, and Mars. Day-to-day operations of the Exolith Lab are managed by Dr. Zoe Landsmen (Chief Scientist) and Anna Metke (Director of Operations). Dr. Landsmen's research focuses on characterizing the surfaces of airless planetary bodies, including the Moon, using observational and laboratory techniques and thermal modeling. Ms. Metke has been involved in the lab since it began with the SBIR grant, has participated in science research for 5 years and business management for 10 years.

Exolith also offers complimentary consulting on simulant-related science to assist in the choice and use of their simulants. At the end of 2019, Exolith updated its equipment for improved production rate and consistency (including using a laser diffraction particle size analyzer) and increased its workforce. In 2021, Exolith moved their operations to a new, larger facility that provides improved climate control and allows for additional storage and larger batch production. The Exolith Lab has also performed an extensive overhaul of their website to provide greater transparency concerning their products and source rocks used in simulant production.

Simulants Tested and Available Simulants

The Exolith lab makes a range of simulants for asteroids (CI, CM, and CR), Mars (MGS-1, MGS-1S, MGS-1C, and JEZ-1), and the Moon (lunar highland LHS-1 and lunar mare LMS-1). Rather than using a single lithology as their starting point, Exolith mixes individual minerals and lithic fragments in varying proportions to match lunar soil compositions.

In 2021, Exolith adopted changes to the feedstocks used to create their simulants. Previously, the anorthosite component was derived from the Stillwater Anorthosite. Exolith now uses White Mountain Anorthosite mined in Kangerlussuaq, Greenland (aka GreenSpar) from Hudson Resources, Inc. The GreenSpar anorthosite has a plagioclase content of 82–94 wt% with an average anorthite number (An#) of 83 (Gruener et al., 2020). The team changed to this component in 2021 to improve chemical fidelity and supply chain quantities. In addition, in 2021 they changed the glass-rich basalt source from the commercially-available Black Lava Rock from Pebble Junction (Sanford, FL) because it was no longer available. The new glass-rich basalt is also a commercially-available product that was selected for its' similarity to Black Lava Rock. At the time of this writing, the provenance is not clear because the commercial company has been reluctant to reveal the source mine. Company representatives did sate that they are transitioning to using the glass-rich basalt from Merriam Crater, which was the basalt source used for JSC-1A. Detailed analyses with X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) of source components are provided in their report entitled "Exolith Simulants Constituents Report" available on their website. We note that the simulant we received from the NASA LSII Simulants Team for this year's analysis was purchased in October of 2020 and it contains Stillwater Anorthosite and Black Lava Rock feedstocks rather than the feedstocks currently used by Exolith. Simulant users should be cognizant of when their Exolith simulant was produced and what feedstocks were included so they can account for possible variations.

According to the Exolith spec sheet, the Exolith lunar highland simulant LHS-1 is primarily composed of GreenSpar anorthite (74.4 wt.%) with 24.7% glass that is a basaltic cinder that matched closely in terms of mineralogy and glass content to the previous black lava rock. Although it is not a close compositional match to the lunar highlands, it does provide a reasonable analog for the mare basalt contamination found in Apollo 16 samples due to lateral, impact-induced mixing. The remaining fraction of LHS-1 includes ≤0.5 wt.% each of basalt, ilmenite, pyroxene, and olivine. LHS-1 was evaluated for this assessment (Fig. 5).

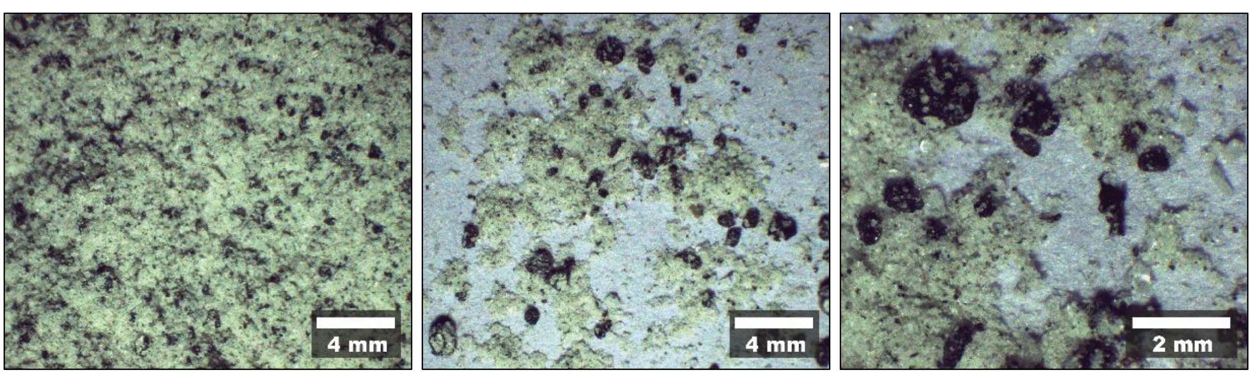

Figure 5: Microscopic images of unsieved Exolith LHS-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of LHS-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of LHS-1 simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of LHS-1 simulant.

The Exolith lunar mare simulant LMS-1 is intended to be representative of low- to moderate-titanium (in this case, 7.3 wt% TiO_2) mare. The Exolith spec sheet states that it is comprised of 32.8% pyroxene, 32% glass-rich basaltic, 19.8% plagioclase, 11.1% olivine, and 4.3% ilmenite in proportions based on "average" lunar basalt. For this assessment, we studied their LMS-1 mare simulant (Fig. 6).

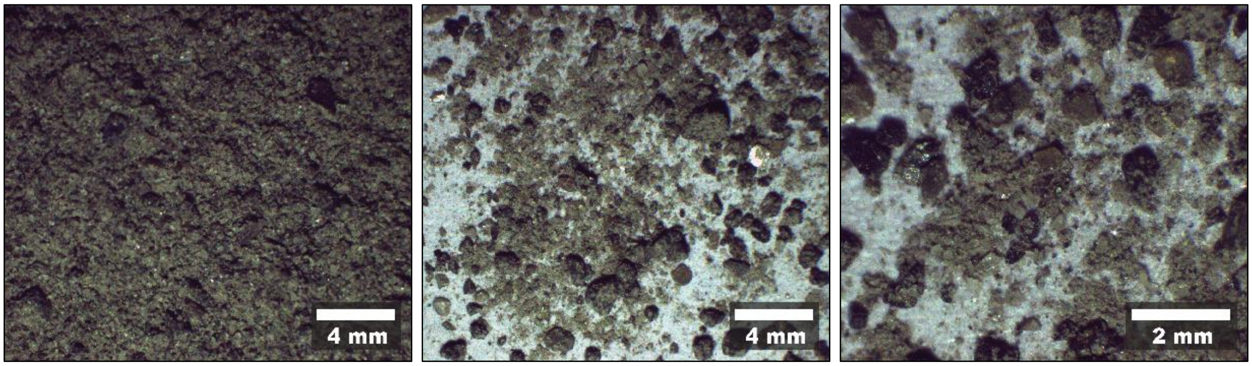

Figure 6: Microscopic images of unsieved Exolith LMS-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of LMS-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of LMS-1 bulk simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of LMS-1 bulk simulant.

Exolith also produces two lunar dust simulants, including one with a highland-based composition (LHS-1D) and another with a mare-based composition (LMS-1D). Both dust simulants have a mean particle size of 7 microns. Currently, this dust simulant is simply the fines created as a by-product during the grinding of materials for other simulants, with limited control on composition; however, if there is a desire for a dust simulant with compositional fidelity, that could be created. Exolith also produces a lunar agglutinated simulants, LHS-1-25A, at their facility using an in-house method to partially melt a small bed of 99% anorthosite mixed with 1% metallic iron, which is then rapidly cooled and processed for grain size. The simulant has been developed as a high-fidelity, mineral-based simulant appropriate for an average highland location on the Moon with intermediate maturity. The simulant is composed of 75% LHS-1 with 25% agglutinated anorthosite by weight. The anorthosite agglutinate can also be purchased separately to mix into any simulant. Exolith simulants do not include nanophase iron.

Particle Size Distribution

By measuring the mass of each sieved fraction of the simulants, we are able to compare the particle size frequency distribution of the simulants with Apollo soil samples (Fig. 7). The particle size distribution determined by weighing sieved grain size splits shows a particle size distribution (PSD) that is within 1 standard deviation of an average of Apollo samples, but the Exolith samples do have a relatively greater abundance of larger particles (>100-500 µm). Our results show a steeper PSD curve due to a much lower abundance of smaller particles (<100 µm) when compared to the Apollo average (Fig. 7).

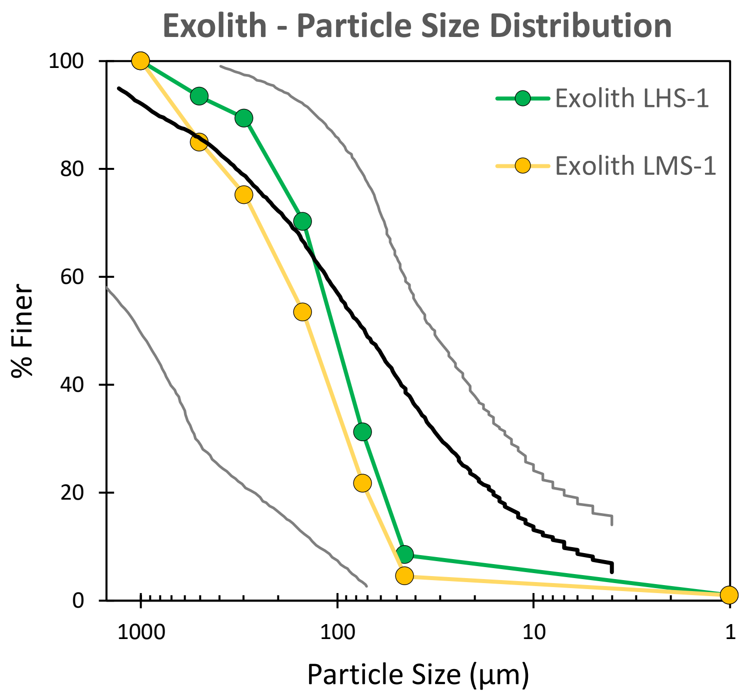

Figure 7: Cumulative particle size distribution of Exolith simulants (green and yellow) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

Minimum and Maximum Density

The minimum and maximum density values measured for all the regolith samples in this study are shown in in Table 2 with these same values for returned lunar samples. The returned lunar samples include regolith from Apollo 11 (Costes et al., 1970a,b; Cremers et al, 1970), Apollo 12 (Cremers and Birkebak, 1971; Jaffe, 1971), Apollo 14 (Cremers et al., 1972; Carrier et al., 1973a,b), Apollo 15 (Cremers and Hsia, 1973; Carrier et al., 19973a,b), Luna 16 (Gromov et al., 1972, Leonovich et al., 1974, 1975) and Luna 20 (Vinogradov, 1972; Ivanov et al., 1973a,b; Leonovich et al., 1974, 1975). The densities were determined in laboratory settings at ambient pressures with air or nitrogen environments, often as part of a larger or related study (e.g., thermal conductivity measurements).

Table 2: Minimum and maximum densities measured for regolith simulants in this study and for lunar samples from various studies.

Producer	Simulant name (type)	ρ min (g/cm³)	ρ max (g/cm³)
Exolith	**LHS-1** (highland)	1.38	1.56
	LMS-1 (mare)	1.58	1.73
Off Planet Research	**OPRH2N** (highland)	1.32	1.50
	OPRL2N (mare)	1.31	1.54
Colorado School of Mines	**CSM-LHT1** (highland)	1.43	1.57
	CSM-LMT1 (mare)	1.50	1.76
Deltion	**OB-1A** (highland)	1.51	1.63
USGS/NASA	**NU-LHT-4M** (highland)	1.50	1.63
Previous Work			
Returned lunar sample data	**Apollo samples**[1]	0.87 - 1.36	1.51 - 1.93
	Luna samples[1]	1.04 - 1.2	1.7 - 1.8

[1]From Table 9.7. of Carrier et al. (1991), showing value range displayed for various Apollo and Luna samples.

The minimum and maximum density values for Exolith lunar regolith simulants are shown in Figure 8 relative to the range of minimum and maximum density values determined from returned samples. Both the LHS-1 highland simulant and the LMS-1 mare simulant have minimum density values that exceed that observed for lunar samples (Fig. 2). This would suggest that the simulants have a closer packing, or less void space, when poured into the cylinder than what is observed for lunar regolith samples. Both the LHS-1 highland simulant and the LMS-1 mare simulant have maximum density values that plot within the range of maximum density values observed for lunar regolith.

Specific Gravity

The specific gravity values measured for all the regolith samples in this study are shown in in Table 3 with these same values for returned lunar samples (after Carrier et al., 1991). The returned Apollo samples include Apollo 11, 12, 14, 15, and 17 samples measured by water pycnometry (Horai and Winkler, 1975; 1976; 1980; Carrier et al., 1973a; 1973b), nitrogen pycnometry (Costes et al., 1970a), helium pycnometry (Cadenhead et al., 1972; 1974; Cadenhead and Stetter, 1975), air pycnometry (Carrier, 1970), and suspension in density gradient (Duke et al., 1970). For this study, we used the water pycnometry method. Based on these studies, the recommended typical specific gravity of lunar soil is 3.1 (Carrier et al., 1991) calculated from the average specific value for Apollo samples.

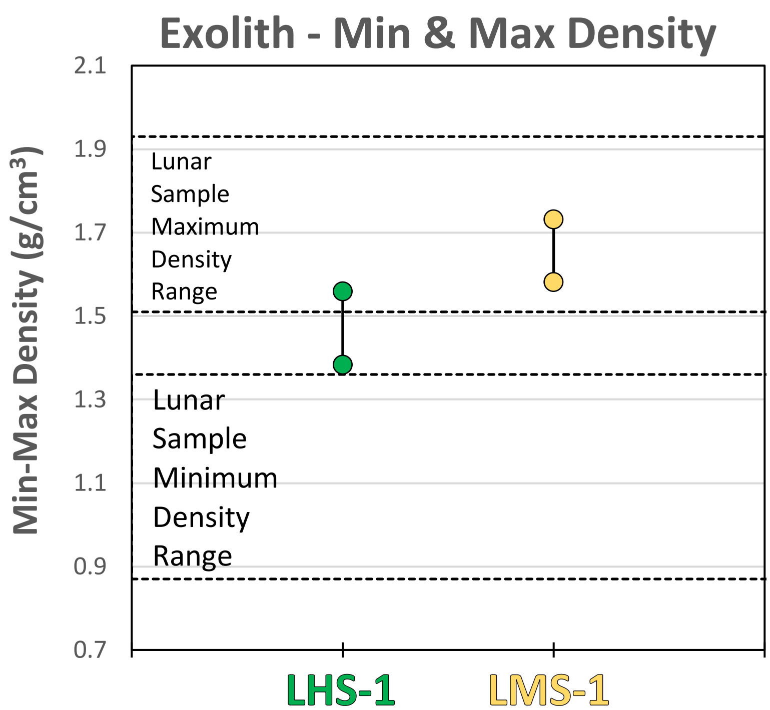

Figure 8: Minimum (bottom circles) and maximum (top circles) densities measured for Exolith regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Table 3: Specific Gravity values measured for regolith simulants in this study and for lunar samples from various studies.

Producer	Simulant name (type)	Specific Gravity
Exolith	**LHS-1** (highland)	2.77
	LMS-1 (mare)	3.00
Off Planet Research	**OPRH2N** (highland)	2.79
	OPRL2N (mare)	2.87
Colorado School of Mines	**CSM-LHT1** (highland)	2.81
	CSM-LMT1 (mare)	2.90
Deltion	**OB-1A** (highland)	3.03
USGS/NASA	**NU-LHT-4M** (highland)	2.89
Previous Work		
Apollo lunar soils average SG and SG range (in parentheses) [1]		3.1 (2.3 - 3.5)

[1]After Table 9.3. of Carrier et al. (1991): Specific gravity average value (recommended specific gravity for lunar soils) and, in parentheses, the range of values measured for soils from Apollo 11, 12, 14, 15, and 17.

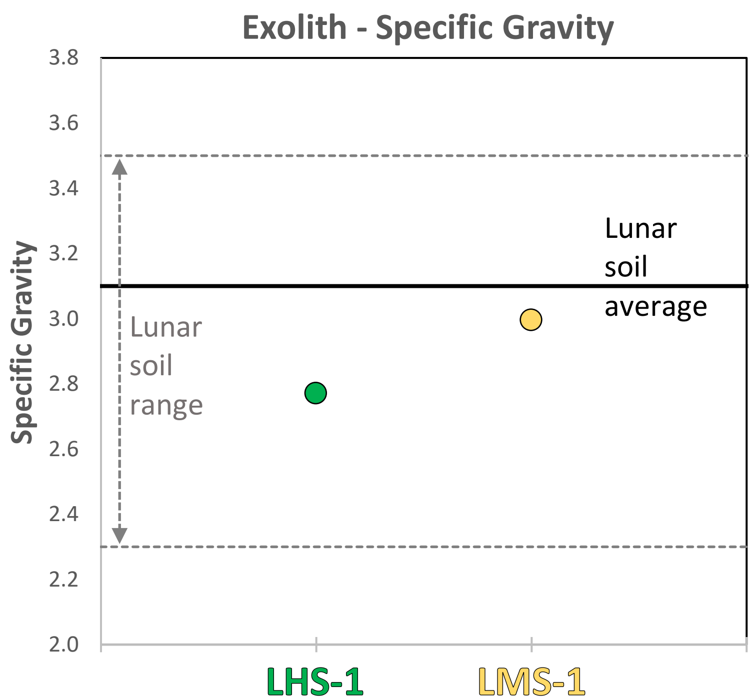

Figure 9: Specific gravities measured for Exolith regolith simulants in this study and lunar soil specific gravity average and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

Direct Shear

The values for cohesion and friction angles determined by this study from the direct shear measurements of lunar regolith simulants are shown in Table 4. Table 4 also lists previous estimates of these values from Surveyor missions (Halajian, 1964; 1966; Jaffe, 1964; 1965, 1967; Nordmeyer, 1967; Moore, 1970; Havland and Mitchell, 1971; Mitchell et al., 1973a; Christensen et al., 1968a; 1968b; Scott and Robertson, 1969) and Apollo missions (Costes et al., 1969; 1971; Scott et al., 1970; Leonovich et al., 1971; 1972; Mitchell et al., 1971; 1972a; 1972b; 1972d; 1973a; 1974) as well as values determined for returned Apollo and Luna lunar samples from various studies (Costes et al., 1969; 1970a; 1970b; Costes and Mitchell, 1970; Jaffe 1971, 1973; Carrier et al., 1972b, 1973c; Gromov et al., 1972; Leonovich, 1974a; 1975; Scott, 1987). Studies on returned samples involved measurements done under vacuum as well as under ambient pressures in air and in nitrogen; for comparison to this work, we focused on direct shear measurements done under ambient conditions. Table 4 also includes the recommended typical values for lunar soil cohesion and friction angles for intercrater areas of Carrier et al. (1991) by depth.

Table 4: Cohesion and friction angle determined for lunar regolith simulants from direct shear measurements and previous estimates.

Producer	Simulant name (type)	Cohesion (kPa)	Friction Angle (°)
Exolith	**LHS-1** (highland)	11	35
	LMS-1 (mare)	10	37
Off Planet Research	**OPRH2N** (highland)	12	36
	OPRL2N (mare)	7	40
Colorado School of Mines	**CSM-LHT1** (highland)	12	32
	CSM-LMT1 (mare)	12	36
Deltion	**OB-1A** (highland)	15	35
USGS/NASA	**NU-LHT-4M** (highland)	8	38
Previous estimates			
Surveyor model best estimate[1]		0.35 – 0.70	35 - 37
Apollo model best estimate[2]		0.1 – 1.0	30 - 50
Returned lunar samples[3]		0.1 – 5.9	13 - 56
Recommended typical values for intracrater areas[4]	**0 – 15 cm**	0.52 (0.44 – 0.62)	42 (41 – 43)
	0 – 30 cm	0.90 (0.74 – 1.1)	46 (44-47)
	30 – 60 cm	3.0 (2.4 – 3.8)	54 (52 – 55)
	0 – 60 cm	1.6 (1.3 – 1.9)	49 (48 – 51)

[1]Scott and Roberson (1969); [2]Mitchell *et al*. (1972d, 1974); [3]As compiled in Table 9.11. in Carrier *et al*. (1991); [4]From Table 9.12. of Carrier *et al*. (1991), which included values for average and ranges (ranges shown in parentheses).

The cohesion values determined from direct shear measurements for the Exolith simulants (Table 4) exceed the values measured for returned lunar samples (Table 4, Fig. 10). In fact, both simulants have cohesion values that are nearly double the upper limit measured for returned lunar samples. However, the friction angles determined from direct shear measurements for the Exolith simulants (Table 4) plot well within the range of values determined for returned lunar samples (Table 4, Fig. 10).

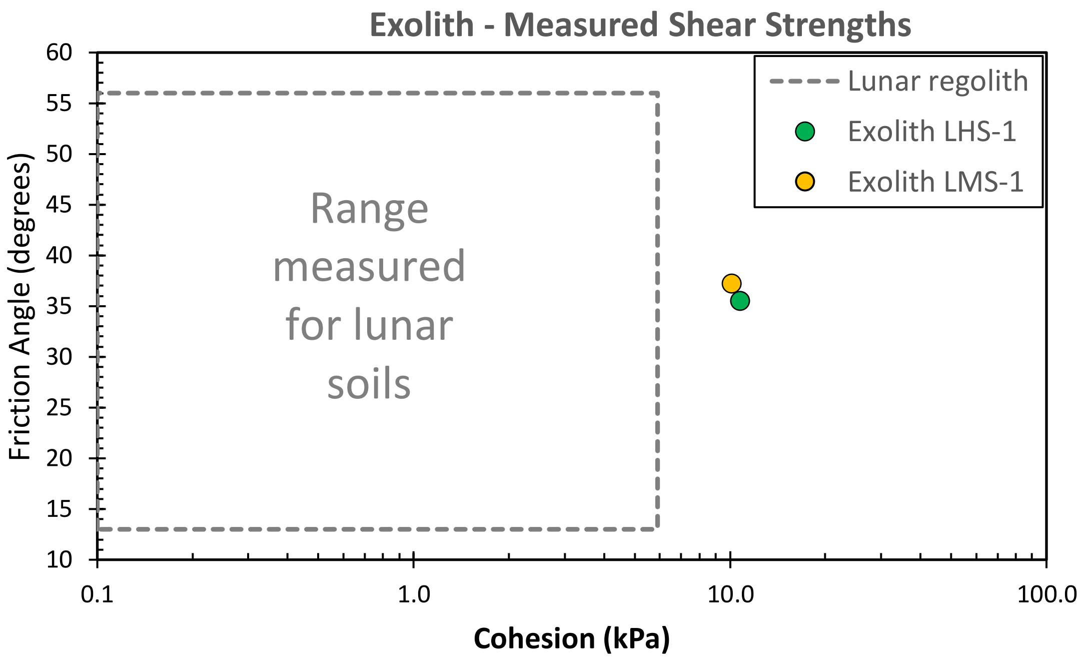

Figure 10: Friction Angles vs. Cohesion determined from direct shear measurements of Exolith regolith simulants in this study and the range of lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Supply Chain and Quality Control

Exolith simulants can be purchased directly online and company representatives stated that they continue to make improvements to their website, including providing more detailed information through publications on their regolith simulants. They emphasized that they are committed to publishing their results and updating properties in scientifically-reviewed literature. Since their move to a larger facility in 2021, Exolith is able to manufacture up to 1 tonne of simulant material every day and they are currently providing 100 kg of regolith simulant to research and education communities every week. This production rate has been met with growth of their company, and they now have over 30 paid employees and a team of 25 high school volunteers. The high school volunteer program allows students to participate in the manufacturing, distribution, and research operations to receive credit for college scholarships and many of their students have been accepted to universities to pursue STEM degrees. In addition the company is also expanding into regolith test beds that will contain their lunar highland simulant for testing initially, with the capability to have sectioned testing with other simulants.

Exolith does employ some quality control techniques during production process. The composition of the batch source material is verified with XRF and XRD analyses when it arrives at their facility; XRF and XRD analyses are also conducted on final simulant mixtures every two months to assure accuracy. In addition, they do sieve analysis and laser diffraction on constituent minerals and simulant products monthly to assure consistent particle size. Exolith has also worked hard to standardize their simulant production process in order to improve their quality control. The bulk chemistry, XRD and XRF analyses of their simulants are present in their spec sheets, but is not verified for each batch. The oxide values reported in the spec sheets do match fairly well to those determined for our previous study (Stockstill-Cahill et al., 2021), suggesting that there is a general consistency between the batch we received and previous batches assessed by Exolith.

SIMULANT PROVIDER: OFF PLANET RESEARCH

Company Background

Off Planet Research (OPR) is a small for-profit business located in Everett, Washington (after relocating from Lacey, WA in 2021). The company was originally founded in 2015 to develop technologies for future lunar exploration. In order to better test these technologies, accurate simulants were necessary, and so production of simulants began. Off Planet Research is managed by Melissa Roth and Vincent Roux. The goals of the company include creating high-quality lunar simulants, development of non-standard simulants for specialized research, testing components and new technologies for inclusion in future lunar missions, and performing fundamental scientific and engineering research in house. They currently produce a wide range of simulant, based on customer needs, and are working to expand their customer base and capabilities.

Simulants Tested and Available Simulants

Off Planet Research offers a variety of lunar simulants based on two feedstocks: Archean anorthosite from the Shawmere Anorthosite Complex in Ontario, Canada (An_{78}; Battler and Spray, 2009) and basaltic cinder from the San Francisco volcanic field in Arizona, and ilmenite. These feedstocks are crushed to mimic the particle shapes and particle-size distribution of lunar soils and are combined in varying proportions for their standard simulants, or in proportions that can be customized to meet user needs. The standard simulants are designed to follow the average Apollo 17 particle size distribution unless otherwise requested by the customer.

The Off Planet standard lunar highland simulants include OPRH2N (70% anorthosite, 30% basaltic cinder) and OPRH3N (80/20 anorthosite/basaltic cinder) as reported by the company, to mimic nearside and farside lunar highlands, respectively. (We note that no lunar highland regolith samples have been collected from the farside, and a 20% basaltic component may be too high, though the percentage can be adjusted during creation.) In addition, they produce a highland simulant called OPRH4N (90% anorthosite, 10% basaltic cinder) that represents a high anorthosite lunar highland material. Agglutinates can be added upon request. Only OPRH2N was evaluated for this assessment (Fig. 11).

The Off Planet standard mare simulants include OPRL2N (90% basaltic cinder, 10% anorthosite) and OPRL2NT (77% basaltic cinder, 8.6% anorthosite, 14.4% ilmenite) as reported by the company; OPRL2NT has ilmenite added to mimic high-titanium mare materials. Agglutinates can be added upon request. Only OPRL2N was evaluated for this assessment (Fig. 12).

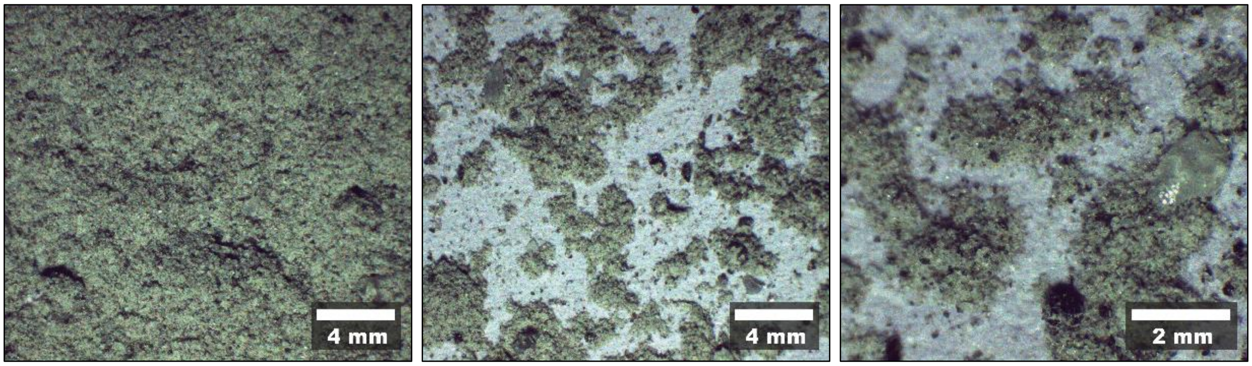

Figure 11: Microscopic images of unsieved OPRH2N simulant used for testing. **(Left)** Low magnification (0.75x) overview image of OPRH2N bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of OPRH2N simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of bulk OPRH2N simulant.

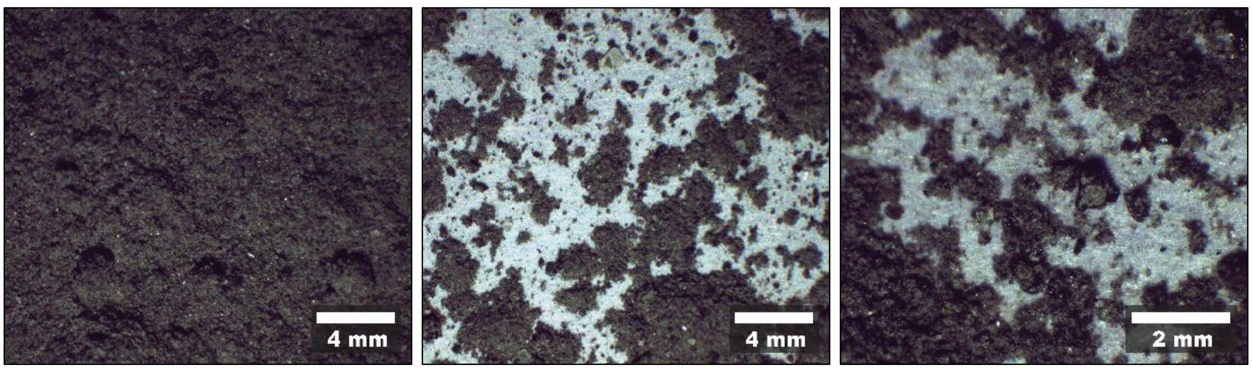

Figure 12: Microscopic images of unsieved OPRL2N simulant used for testing. **(Left)** Low magnification (0.75x) overview image of OPRL2N bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of OPRL2N simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of OPRL2N simulant.

Off Planet Research also produces agglutinate simulant in bulk, which are created from the base simulants and thus share the same chemical compositions. These agglutinate simulants are provided separately and left to the user to mix with a base simulant in desired quantities. Their method for agglutinate production is proprietary and was described to us only in limited terms in a conference publication (they “replicate the natural formation process by micro-meteorite strike” (Roux and Roth, 2017)). The agglutinate simulant was not evaluated for this assessment.

In addition, Off Planet Research produces an icy regolith simulant named OPRFLCROSS2, which has a volatile composition based on LCROSS measurements (Colaprete et al., 2010). For this simulant, ice components are deposited onto super-cooled regolith simulant particles in an effort to mimic the deposition process of lunar polar ices in and on lunar regolith particles (Roux et al., 2019). The chemical composition of OPRFLCROSS2 can include water, carbon dioxide, carbon monoxide, hydrogen sulfide, sulfur dioxide, methane, ethane, ammonia, and methanol (Roax et al., 2019). The presence of ices has been shown to have a notable effect on the mechanical properties of the soils (Roux et al., 2022). The icy simulant can be produced and experimented upon at the Off Planet Research facility or at the clients facilities depending upon the composition requested. The icy simulant was not evaluated for this assessment.

Finally, Off Planet Research has recently added an Increased Magnetic Response Simulant (Roth et al., 2022) to their portfolio due to requests from customers. This simulant mechanically creates an iron-rich rim that approximates the embedded iron in lunar mineral rims that is not naturally found in lunar simulants. A company representative noted that customer requests tend to be geared towards lunar highland simulants because terrestrial anorthosites have little iron and the highland simulants include only small amounts of terrestrial basalt that would contribute Fe-bearing magnetic mineralogy. However, any base simulant can be designed with a higher magnetic response. The increased magnetic response simulant were not evaluated.

Particle Size Distribution

The particle size distributions determined by weighing sieved grain size splits for Off Planet Research simulants show a PSD curves that are within 1 standard deviation of an average of Apollo samples (Fig. 13), but the OPR samples do have a somewhat greater abundance of largest particles (>500 µm). Our results show a steeper PSD curve between 40 and ~150 µm due to a much lower abundance of smaller particles (<74 µm), but appear to be a good match to the smallest particle sizes (Fig. 13). We note that we have excellent match between the PSDs of the OPRH2N highland simulant and the OPRL2N mare simulant, indicating overall consistency in the particle size produced between batches (Fig. 13).

Minimum and Maximum Density

The minimum and maximum density values for Off Planet Research lunar regolith simulants (Table 2) are shown in Figure 14 relative to the range of minimum and maximum density values determined from returned samples. Both the OPRH2N highland simulant and the OPRL2N mare simulant have minimum density values at the upper range observed for lunar samples (Fig. 14). This would suggest that the simulants have similar packing when poured into the cylinder than what is observed for lunar regolith samples. The OPRH2N highland simulant has a maximum density value (1.50) that is just below the maximum density range observed for lunar regolith (1.51 – 1.93); however, the maximum density of the OPRL2N mare simulant does fall within the range of maximum density values observed for lunar regolith.

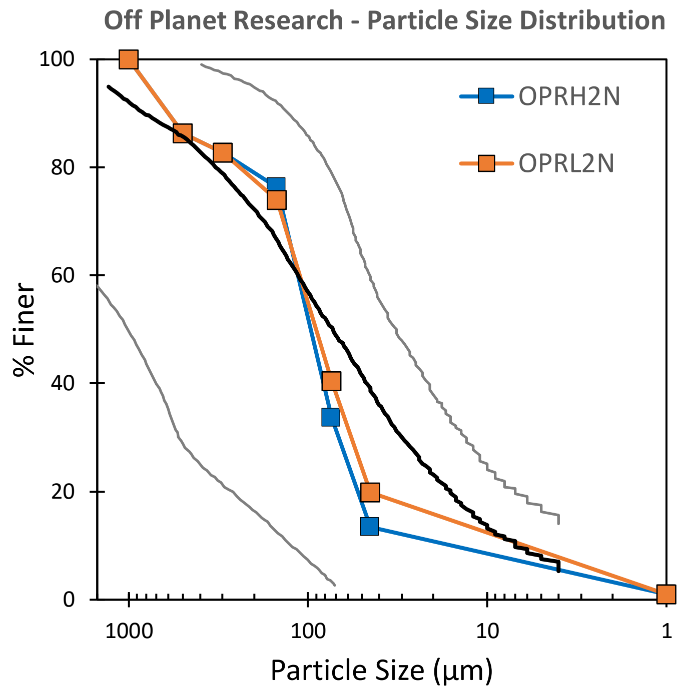

Figure 13: Cumulative particle size distribution of Off Planet Research simulants (orange and blue) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

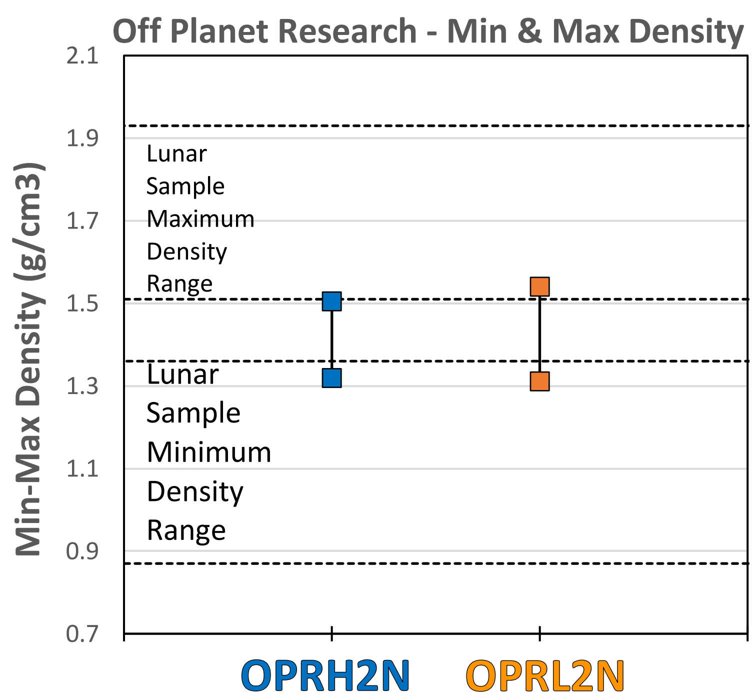

Figure 14: Minimum (bottom squares) and maximum (top squares) densities measured for Off Planet Research regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Specific Gravity

As shown in Figure 15, the specific gravity values measured for the Off Planet Research lunar regolith simulants (Table 3) plot within the range measured for various lunar soils (Carrier et al., 1991). Both the highland simulant OPRH2N and the mare simulant OPRL2N plot below the average specific value of Apollo samples and recommended typical specific gravity value of Carrier et al. (1991). We note that the highland simulant OPRH2N has a lower specific gravity than that of the mare simulant OPRL2N for the Off Planet Research simulants (Fig. 15).

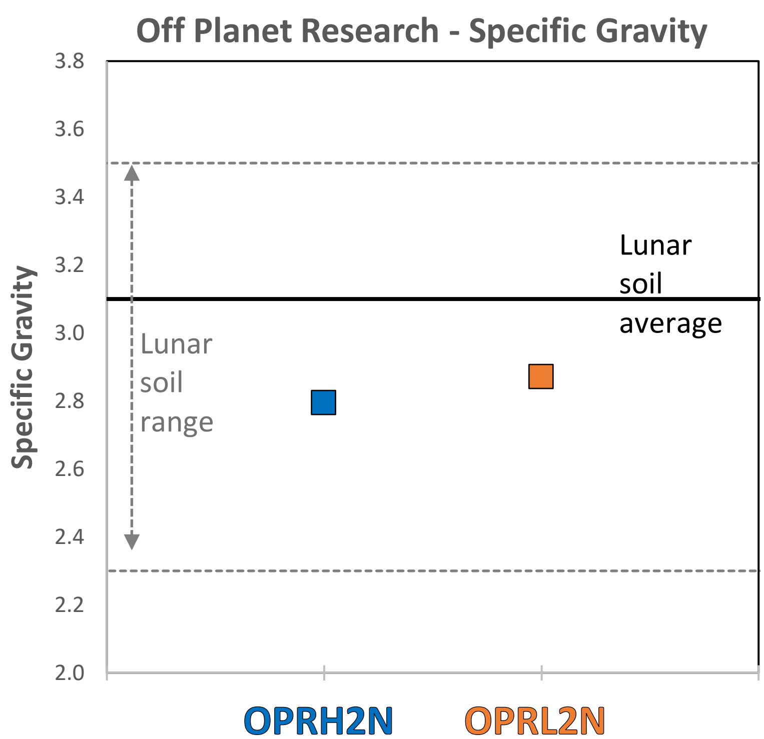

Figure 15: Specific gravities measured for Off Planet Research regolith simulants in this study and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

Direct Shear

The cohesion values determined from direct shear measurements for the Off Planet Research simulants (Table 4) exceed the values measured for returned lunar samples (Table 4, Fig. 16). The highland simulant OPRH2N has a cohesion value that is double the upper limit measured for returned lunar samples; whereas the mare simulant OPRL2N has a cohesion value just above the upper limit and has the closest cohesion value for simulants included in this work. Furthermore, the friction angles determined from direct shear measurements for the Off Planet Research

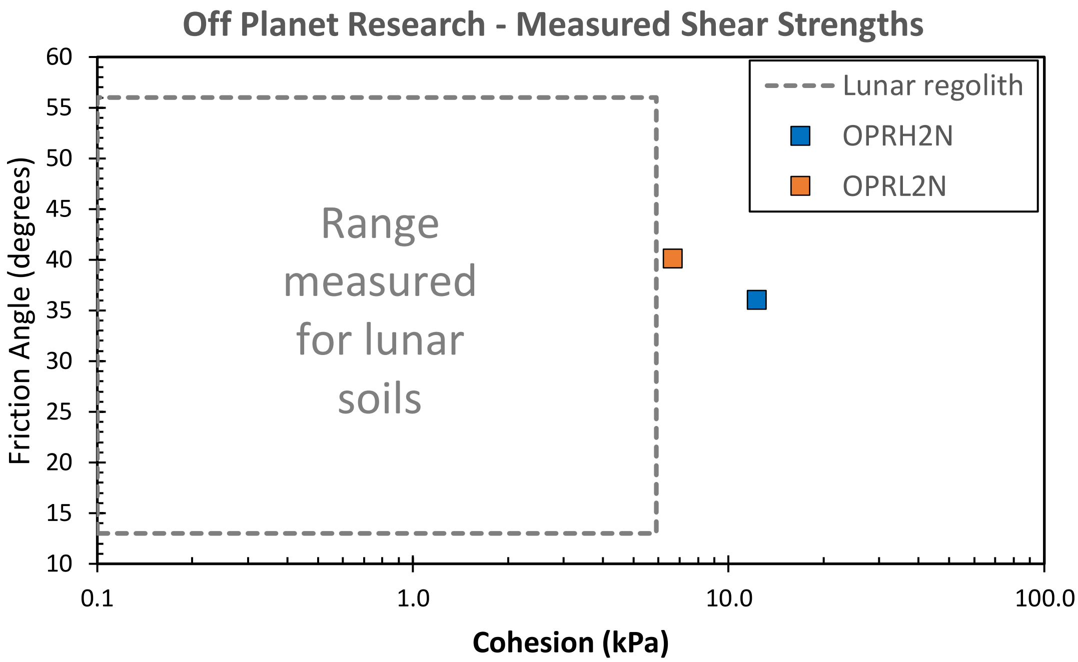

Figure 16: Friction Angles vs. Cohesion determined from direct shear measurements of Off Planet Research regolith simulants in this study and the range of lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

simulants (Table 4) plot well within the range of values determined for returned lunar samples (Table 4, Fig. 16).

Supply Chain and Quality Control

Off Planet Research representatives Vince Roux and Melissa Roth state that the feedstocks can be mixed in proportions and particle-size distributions tailored to their customers' needs. Their production rate is 60 kg/day for the highland and mare simulants and 2.5 kg/day for agglutinates. Specialty simulants, especially those with additives, do have longer lead times. A company representative noted that smaller orders may take longer due to assembly time than the bulk production rates and the number of pre-existing orders. This is also true for specialty simulants (e.g., magnetic simulants) so they have sufficient time to discuss necessary additives and produce the simulant. They continue to increase their production rates to scale with industry needs.

Off Planet Research institutes rigorous quality control during simulant generation. All steps to generate a specific desired particle size distribution are triple checked prior to simulant generation. Detailed records and library samples are kept of all delivered simulants to ensure repeatability and predictability. Independent analysis, including XRF analysis for chemistry, is performed on feedstocks and additives. Currently, analysis of particle size distribution is usually done in house, but further outside testing and validation can be performed on the simulants if the client asks. The lead researchers state that they want to be flexible and can tailor processes and simulants to customer needs. Prior to simulant generation, several consultations are done with the customer and Off Planet Research to ensure that the simulant is designed and constructed to be appropriate for its intended use.

SIMULANT PROVIDER: COLORADO SCHOOL OF MINES

Company Background

Lunar simulant production at the Colorado School of Mines (CSM) began relatively recently (2021); however, the university has a long history of producing geotechnical simulants for terrestrial applications. The lunar planetary regolith simulant production group is led by Dr. Kevin Cannon and fits within the large infrastructure already in place. The simulant production facility utilizes the CSM simulant heritage and machinery already in the Earth Science Department to create their simulants. The CSM team spent early 2021 prototyping the simulant production process and fine tuning their simulant compositions, shipping their first order in June of that year. Their goal is to provide high fidelity simulants with good quality control and consistency across batches. CSM is also host to the Planetary Simulants Database, that contains regolith simulant information for a range of products.

Simulants Tested and Available Simulants

Colorado School of Mines currently produces several planetary simulants, including simulants for Mars (CSM-MGS-1, CSM-MGS-1C, and CSM-MGS-1S) as well as a two lunar geotechnical simulants (CSM-CL, Mooncastle), a lunar highland simulant (CSM-LHT-1), and a mare simulant (CSM-LMT-1). Instead of using a single lithology, CSM mixes lithic fragments in varying proportions to match desired planetary compositions. There are two main rocks used to create lunar simulants. CSM uses the White Mountain Anorthosite (aka GreenSpar) from Kangerlussuaq, Greenland, which is custom-milled by the supplier to have the appropriate grain size distribution to mimic the Apollo soils (including particles >250 microns). CSM also uses an ash mined from a commercial basaltic cinder quarry near the southern flank of Merriam Crater, Arizona (JSC-1A feedstock source). The basaltic material is crushed at CSM to the appropriate grain size.

The CSM lunar highland simulant CSM-LHT-1 (Fig. 17) is primarily composed of GreenSpar Anorthosite (70%), which is made up of 82-94% plagioclase with a composition of An_{83} (Gruener *et al*., 2020). The remaining 30% is composed of the Merriam Crater basaltic cinder. The bulk composition and mineralogy of this basaltic cinder is generally similar to Apollo 14 soils, although the mineralogy differs due to the oxidizing conditions under which the rock crystallized and subsequently weathered (McKay *et al*., 1994).

The CSM mare simulant CSM-LMT-1 (Fig. 18) represents a low- to moderate-titanium mare and is entirely composed of the Merriam Crater basaltic cinder. This basaltic cinder consists of a

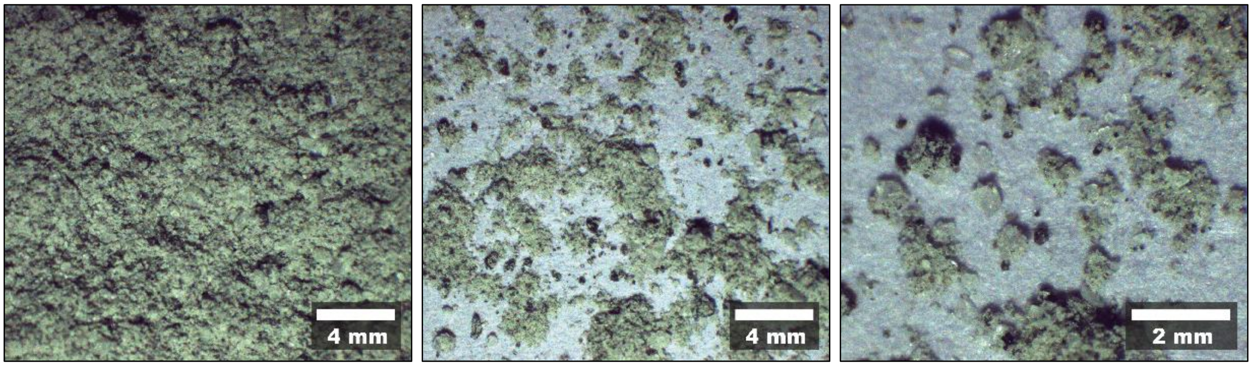

Figure 17: Microscopic images of unsieved CSM-LHT-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of CSM-LHT-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of CSM-LHT-1 simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of CSM-LHT-1 simulant.

mixture of minerals and glassy materials. It has a fine-grained groundmass of predominantly plagioclase laths (andesine, An_{41-48}) with smaller clinopyroxene, olivine, and ilmenite crystals; while larger (0.5-1.55 mm) olivine crystals exist throughout the flow (Hanson, 2008). CSM does not include nanophase iron in any of their simulants or produce synthetic agglutinates.

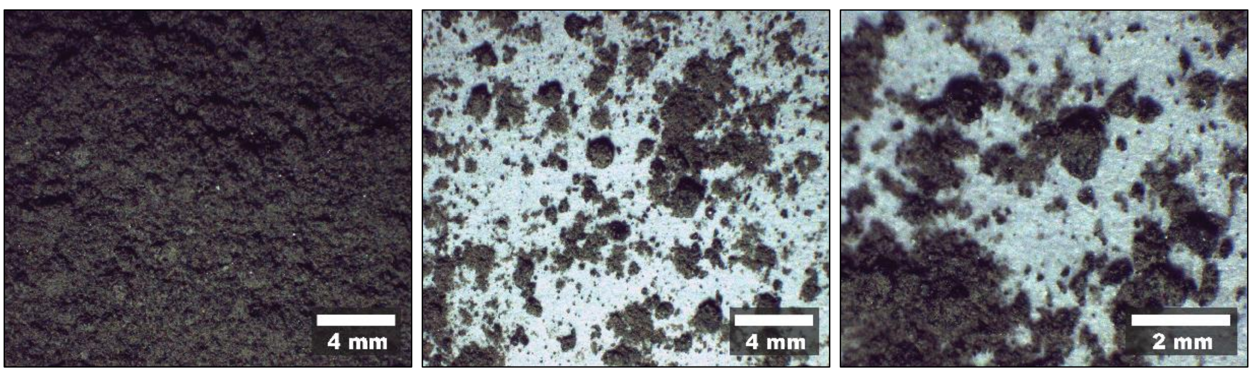

Figure 18: Microscopic images of unsieved CSM-LMT-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of CSM-LMT-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of CSM-LMT-1 simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of CSM-LMT-1 simulant.

Particle Size Distribution

The particle size distributions determined by weighing sieved grain size splits for Colorado School of Mines simulants show PSD curves that are within 1 standard deviation of an average of Apollo samples (Fig. 19), and a fairly good match to abundances of the larger particles (>~150 µm). Our results show a steeper PSD curve between 40 and ~150 µm due to a much lower abundance of smaller particles (<100 µm). In particular, the PSD curve of both simulants show a very low abundance of the smallest particles sizes (<50 µm) relative to the Apollo average (Fig. 19). We also note that we have excellent match between the PSD curves for the CSM-LHT-1 highland simulant and the CSM-LMT-1 mare simulant, indicating overall consistency in the particle size produced between batches (Fig. 19).

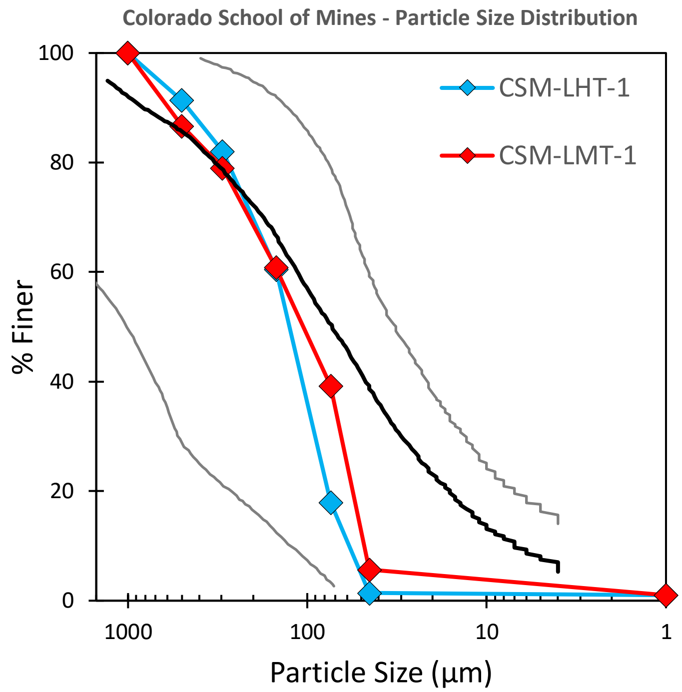

Figure 19: Cumulative particle size distribution of Colorado School of Mines simulants (light blue and red) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

Minimum and Maximum Density

The minimum and maximum density values for Colorado School of Mines lunar regolith simulants (Table 2) are shown in Figure 20 relative to the range of minimum and maximum density values determined from returned samples. Both the CSM-LHT-1 highland simulant and the CSM-LMT-1 mare simulant have minimum density values that exceed that observed for lunar samples (Fig. 20). This would suggest that the simulants have a closer packing, or less void space, when poured into the cylinder than what is observed for lunar regolith samples. Both the CSM-LHT-1 highland simulant and the CSM-LMT-1 mare simulant have maximum density values that plot within the range of maximum density values observed for lunar regolith (Fig. 20).

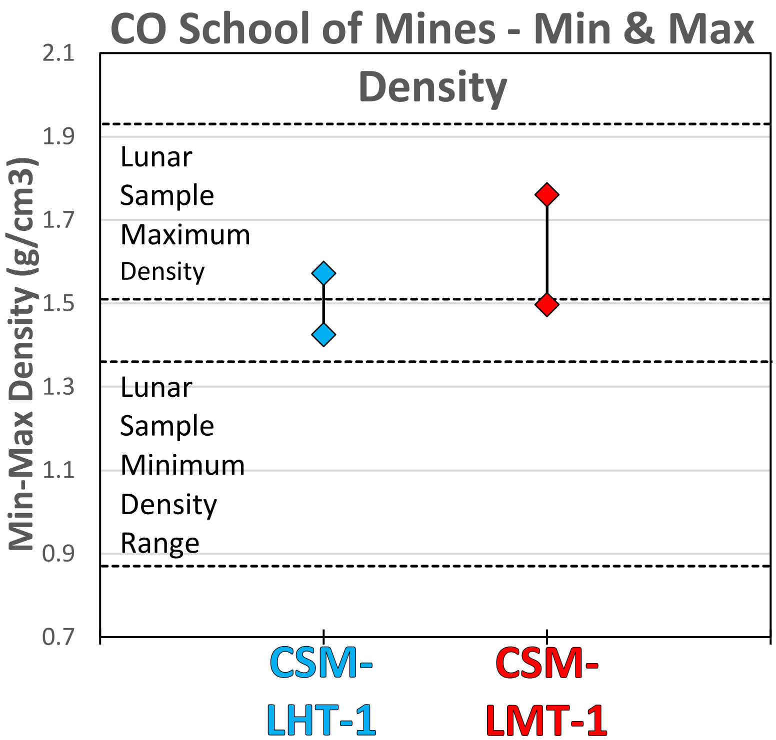

Figure 20: Minimum (bottom diamonds) and maximum (top diamonds) densities measured for Colorado School of Mines regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Specific Gravity

As shown in Figure 21, the specific gravity values measured for the Colorado School of Mines lunar regolith simulants (Table 3) plot within the range measured for various lunar soils (Carrier et al., 1991). Both the highland simulant CSM-LHT-1 and the mare simulant CSM-LMT-1 plot below the average specific value of Apollo samples and recommended typical specific gravity value of Carrier et al. (1991). We note that the highland simulant has a lower specific gravity than that of the mare simulant for the Colorado School of Mines simulants (Fig. 21).

Direct Shear

The cohesion values determined from direct shear measurements for the Colorado School of Mines simulants (Table 4) exceed the values measured for returned lunar samples Table 4, Fig. 22). In fact, both simulants have cohesion values that are more than double the upper limit measured for returned lunar samples. However, the friction angles determined from direct shear measurements for the Colorado School of Mines simulants (Table 4) plot well within the range of values determined for returned lunar samples (Table 4, Fig. 22).

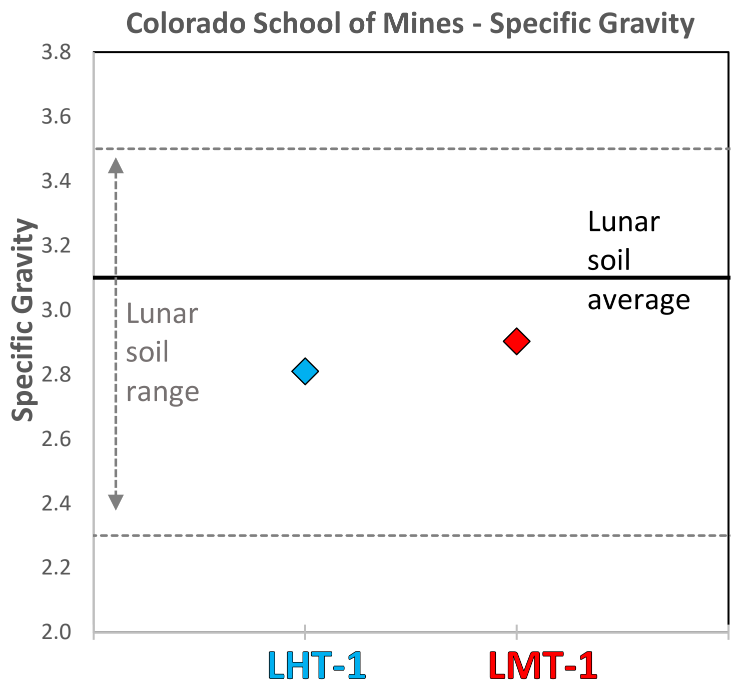

Figure 21: Specific gravities measured for Colorado School of Mines regolith simulants (this study) and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

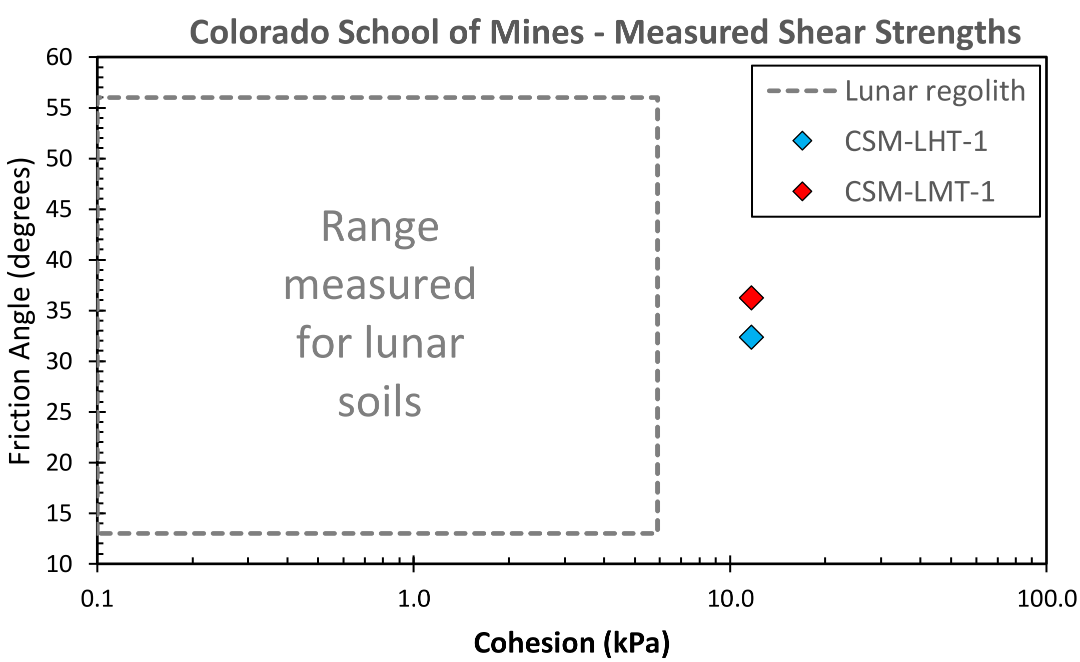

Figure 22: Friction Angles vs. Cohesion determined from direct shear measurements of Colorado School of Mines regolith simulants in this study and the range of lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Supply Chain and Quality Control

In 2021, CSM had ~20 tons each of the GreenSpar Anorthosite and the Merriam Crater basaltic cinder and did not anticipate supply chain issues in the future. In 2021, CSM was able to produce batches of ~125 kg in ~3 hours, which translates to ~1.8 tons per week or tens of tons per year. In the summer of 2021, CSM had requests for ~1.5 tons of lunar simulants; updated capabilities were not available for this assessment. CSM also strives to make the simulants affordable and offers their lunar simulants starting at $8/kg for bulk amounts (Planetary Simulants Database, 2022) and as low as $3 per kg if sufficient quantities are ordered.

Their goal is to consistently produce high-fidelity simulants and their production process includes validation of each batch. This will assure that every batch is within a “tolerance range” for particle shape, size, mineralogy, and general (geotechnical) behavior. The team is building laboratory capabilities that will enable them to certify their simulants in house, including particle size distribution, particle shape parameters, quantitative mineralogy and bulk chemistry, grain density, and magnetic susceptibility. Upon completion of this development, every batch will be checked. In addition, feedstocks will be evaluated to ensure they match previous simulants in mineralogy and general mechanical behavior and a small sample of each simulant batch is retained by the CSM lab for later evaluation and verification.

SIMULANT PROVIDER: DELTION INNOVATIONS LTD.

Company Background

The OB-1 highland simulant was originally developed by researchers at EVC/NORCAT (now Deltion Innovations Ltd.) and the University of New Brunswick, both in Canada. Deltion is a mining company that specializes in automation and robotics, mining in space, and tech transfer between these two industries. Recently, the Intellectual Property (IP) rights to the OB-1 simulant were sold to MacDonald, Dettwiler & Associates (MDA) in Brampton, Ontario who are currently determining the utility to renewing simulant production (S. Macmahon, *pers. comm*.). MDA is an international space mission partner that specializes in robotics and space operations, satellite systems, and geointelligence.

Simulants Tested and Available Simulants

Until recently, Deltion held the IP rights to the OB-1 and Chenobi simulants. OB-1 is a standard lunar highland simulant containing 42% Fe-rich olivine slag glass and 58% Shawmere Anorthosite (An_{78}) by weight (Battler and Spray, 2009). These feedstocks were crushed to match the particle size distribution of the Apollo 16 regolith sample 64500 to produce an analogue material with the geotechnical properties to benefit the design and testing of drilling, excavation, and construction equipment for future lunar surface operations. (Battler and Spray, 2009). In addition, agglutinate components are produced directly from Shawmere feedstock using a plasma arc technique (Weinstein, 2008) to better match the physical and chemical properties of highland-derived agglutinates; that version of the simulants was named Chenobi (Battler and Spray, 2009). We studied the OB-1A simulant for this work (Fig. 23).

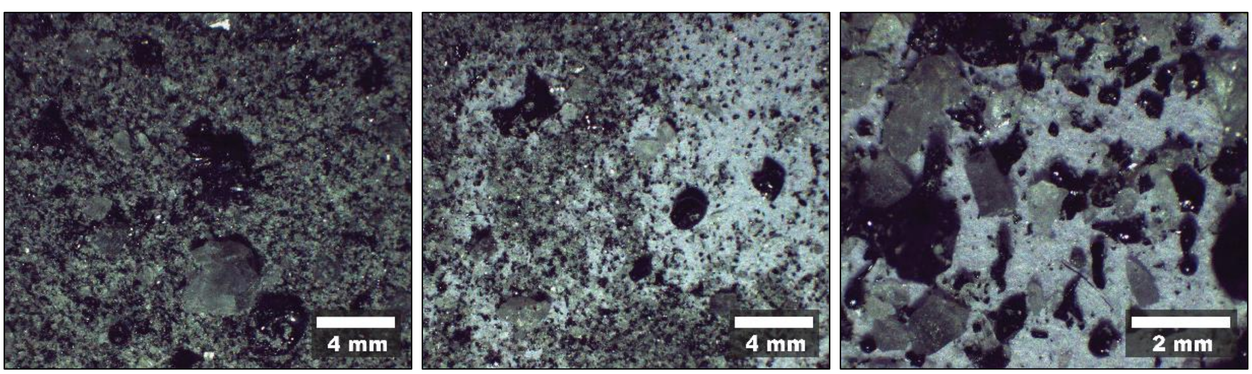

Figure 23: Microscopic images of unsieved OB-1A simulant used for testing. **(Left)** Low magnification (0.75x) overview image of OB-1A bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of OB-1A simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of OB-1A simulant.

Particle Size Distribution

The particle size distribution determined by weighing sieved grain size splits for the Deltion highland simulant OB-1A shows a PSD curve that is within 1 standard deviation of an average of Apollo samples (Fig. 24), and a good match to abundances of the larger particles (≥~150 µm). Our results show a steeper PSD curve between 40 and ~150 µm due to a much lower abundance of particles within this size range, but a better match to the smallest particle sizes (Fig. 24).

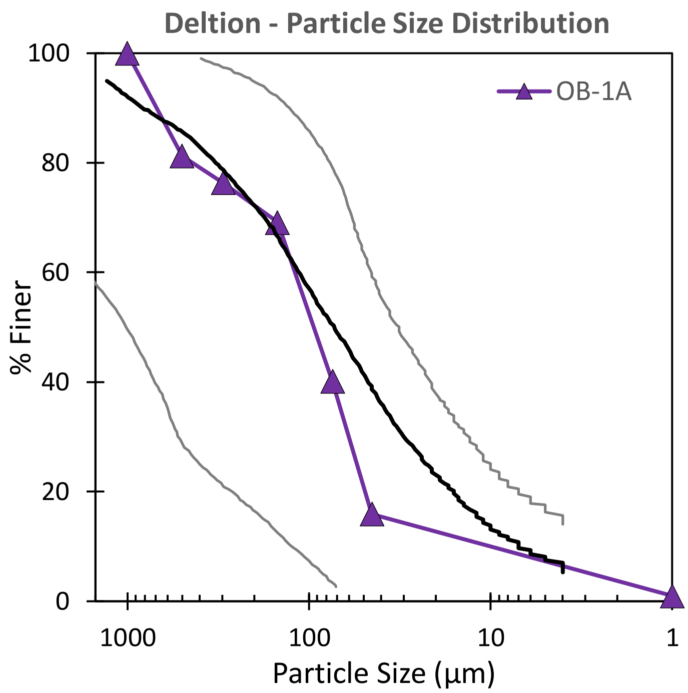

Figure 24: Cumulative particle size distribution of Deltion simulant OB-1A (purple) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

Minimum and Maximum Density

The minimum and maximum density values for Deltion lunar highland regolith simulant OB-1A (Table 2) is shown in Figure 25 relative to the range of minimum and maximum density values determined from returned samples. The OB-1A highland simulant has a minimum density value that exceed those observed for lunar samples (Fig. 25); in fact, it plots just within the maximum density range. This would suggest that the OB-1A simulant has a much closer packing, or less void space, when poured into the cylinder than what is observed for lunar regolith samples. The OB-1A highland simulant has a maximum density values that plot within the range of maximum density values observed for lunar regolith (Fig. 25).

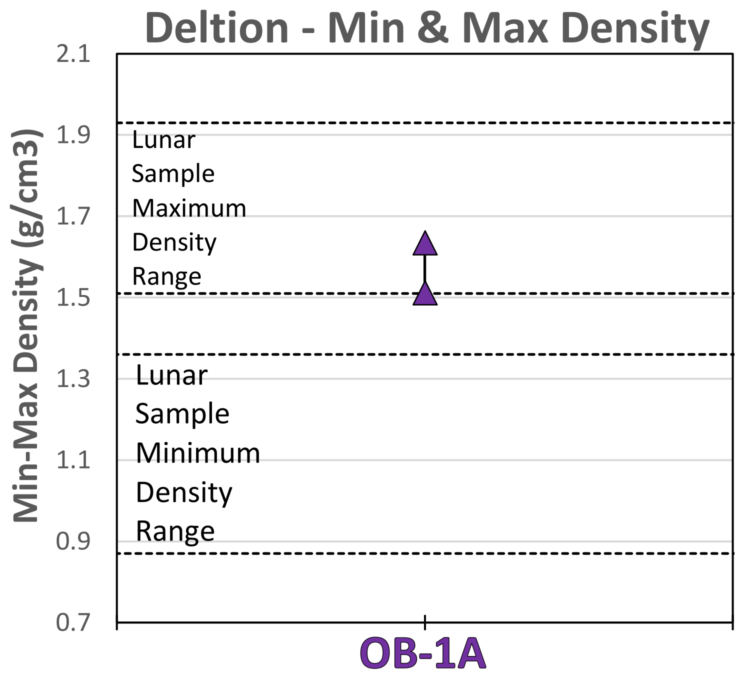

Figure 25: Minimum (bottom triangle) and maximum (top triangle) densities measured for Deltion highland regolith simulant in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Specific Gravity

As shown in Figure 26, the specific gravity value measured for the Deltion lunar highland regolith simulant OB-1A (Table 3) plots within the range measured for various lunar soils (Carrier et al., 1991). The OB-1A simulant plots just below the average specific gravity value of Apollo samples and recommended typical specific gravity value of Carrier et al. (1991). In fact, the OB-1A simulant has the specific gravity value of 3.03 (Table 3), which is the closest to the average specific gravity value of Apollo samples (Fig. 26).

Direct Shear

The cohesion value determined from direct shear measurements for the Deltion highland simulant OB-1A (Table 4) exceeds the values measured for returned lunar samples (Table 4, Fig. 27). In fact, the OB-1A simulant has the highest cohesion value of the simulants examined by this study and is more than double the upper limit measured for returned lunar samples. However, the friction angle determined from direct shear measurements for the Deltion highland simulant OB-1A (Table 4) plots well within the range of values determined for returned lunar samples (Table 4, Fig. 27).

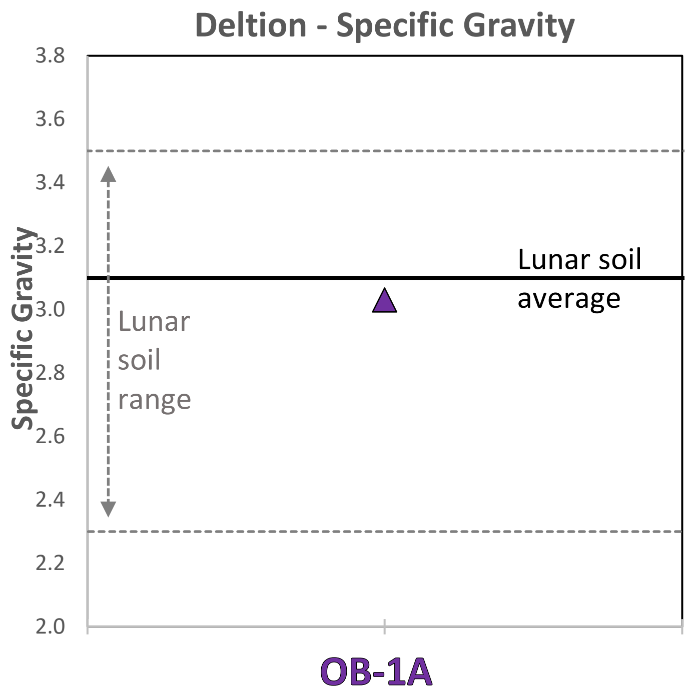

Figure 26: Specific gravity measured for Deltion highland regolith simulant OB-1A and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

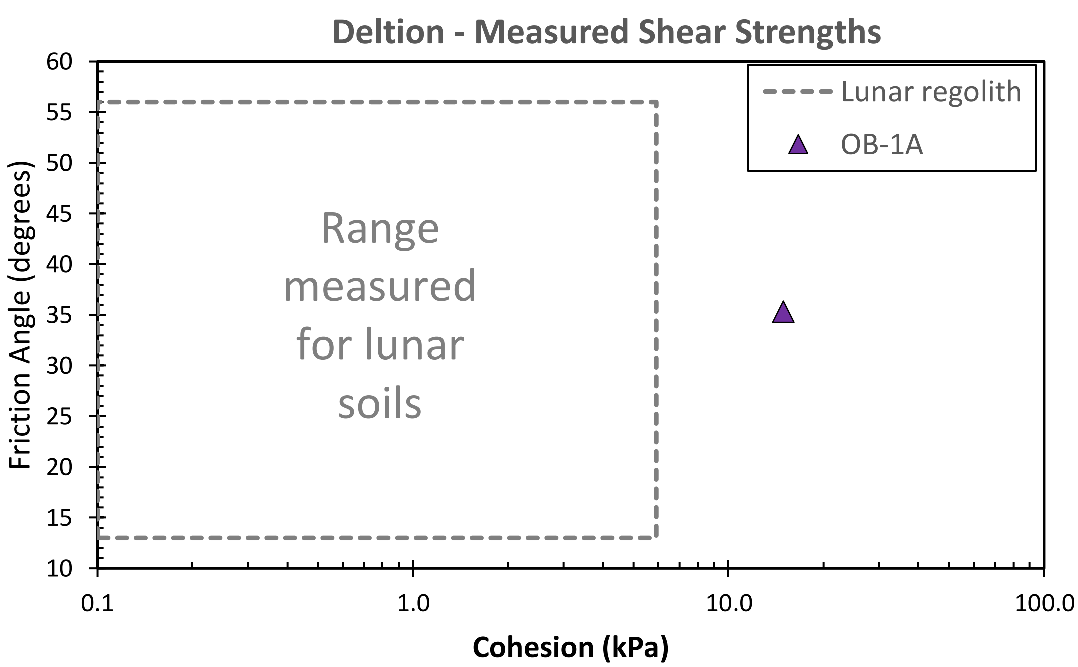

Figure 27: Friction Angles vs. Cohesion determined from direct shear measurements of Deltion highland regolith simulant OB-1A in this study and lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Supply Chain and Quality Control

OB-1A is not currently in production, however the IP rights were recently sold to MDA and their team in determining whether they will restart production of the OB-1A simulant. This will involve determining if there is sufficient demand for the OB-1A simulant and renewing contracts within the simulant supply chain. A company representative did state that they have plans to pull several tons of rock from the mine in Sudbury for an initial production batch and hope to ensure the quality mostly through the production process and final screening of samples. However, their plans are not fully fleshed out at the time the assessment was being written.

SIMULANT PROVIDER: USGS

Company Background

The NU-LHT series was designed by researchers at the United States Geologic Survey (USGS) in collaboration with NASA as a general use lunar highlands simulant (Stoeser et al., 2010). Various versions of the simulants have been developed for many purposes (compositional, mechanical) by adjusting ratios of crystalline materials, pseudo-agglutinates, glass, and finely-ground dust simulant. More recently, researchers have tried to improve the fidelity of the glass component by using both natural and synthetic materials (Rickman et al., 2022).

Simulants Tested and Available Simulants

The NU-LHT series is not currently in mass production, but may be restarted to accommodate the return to the Moon. NU-LHT-1M is composed of 80% crystalline material, 16% pseudo-agglutinate, and 4% "good glass"; NU-LHT-2M contains 65% crystalline material, 30% pseudo-agglutinates, and 5% "good glass" (Stoeser et al., 2010). The NU-LHT-1D is a finely-ground dust simulant and NU-LHT-2C is a synthetic breccia (Schrader et al., 2010). The NU-LHT-3M version lacks the pseudo-agglutinates since it was designed for extensive mechanical testing, which would likely break down the pseudo-agglutinates (D. Rickman, *pers. comm.*). NU-LHT-4M was created by Steve Wilson (USGS) in 2020 to duplicate NU-LHT-2M, but the "good glass" component is currently unavailable; this is offset by increasing the amount of agglutinate glass (J. Gruener, *pers. comm.*). Stillwater 'mill sand' was used as the feedstock for all NU-LHT glass components and has a feldspathic norite composition, see Stoeser et al. (2010). For this study, we examined the geotechnical properties of the NU-LHT-4M (Fig. 28).

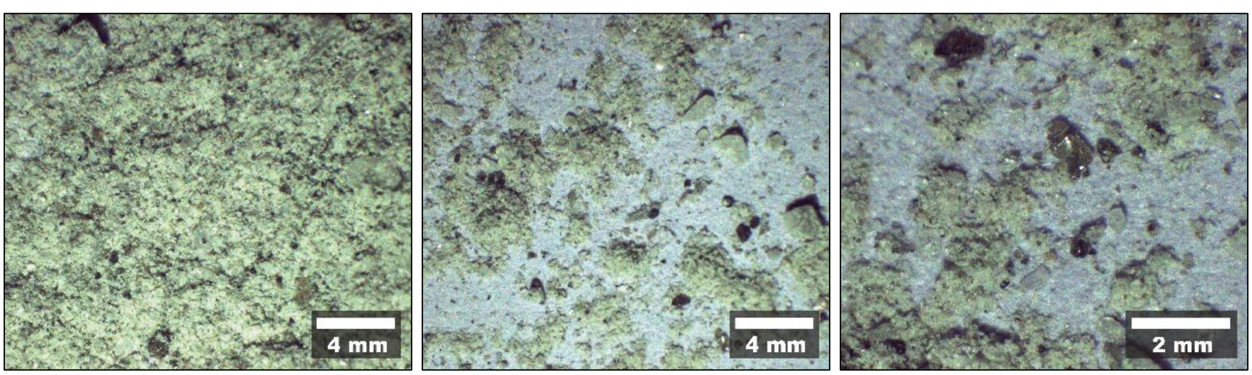

Figure 28: Microscopic images of unsieved NU-LHT-4M simulant used for testing. **(Left)** Low magnification (0.75x) overview image of NU-LHT-4M bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of NU-LHT-4M simulant dispersed onto weighing paper for clarity. **(Right)** Higher magnification (2x) image of the small amount of NU-LHT-4M simulant.

Particle Size Distribution

The particle size distribution determined by weighing sieved grain size splits for the USGS/NASA highland simulant NU-LHT-4M shows a PSD curve that is within 1 standard deviation of an average of Apollo samples (Fig. 29). Our results show a steeper PSD curve overall due to an overabundance of larger particle sizes (>150 µm) and a much lower abundance of smaller particles (>150 µm) (Fig. 29).

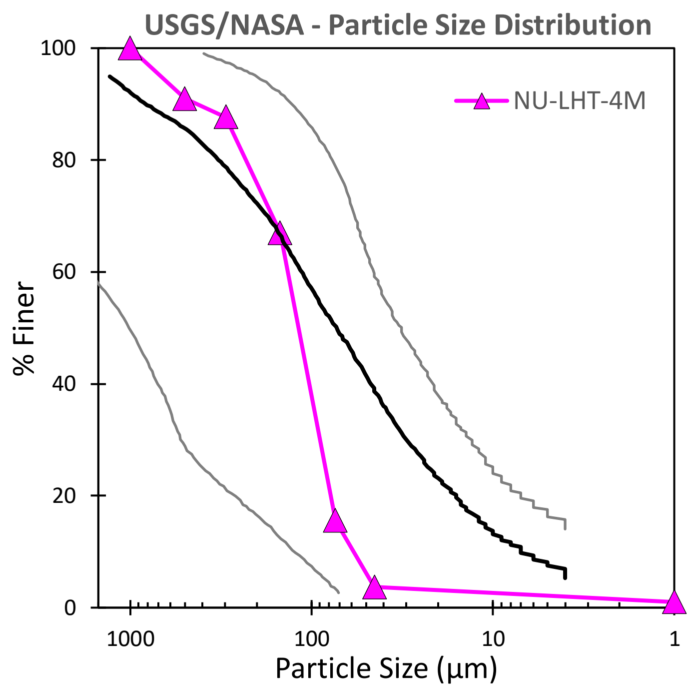

Figure 29: Cumulative particle size distribution of USGS/NASA simulant NU-LHT-4M (magenta) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

Minimum and Maximum Density

The minimum and maximum density values for USGS/NASA lunar highland regolith simulant NU-LHT1-4M (Table 2)are shown in Figure 30 relative to the range of minimum and maximum density values determined from returned samples. The NU-LHT1-4M highland simulant has a minimum density value that exceeds that observed for lunar samples (Fig. 30), plotting just below the range of lunar regolith maximum densities. This would suggest that the uncompacted NU-LHT1-4M simulant has a much closer packing, or less void space, than what is observed for lunar regolith samples. The NU-LHT1-4M highland simulant has a maximum density value that plots within the range of maximum density values observed for lunar regolith (Fig. 30).

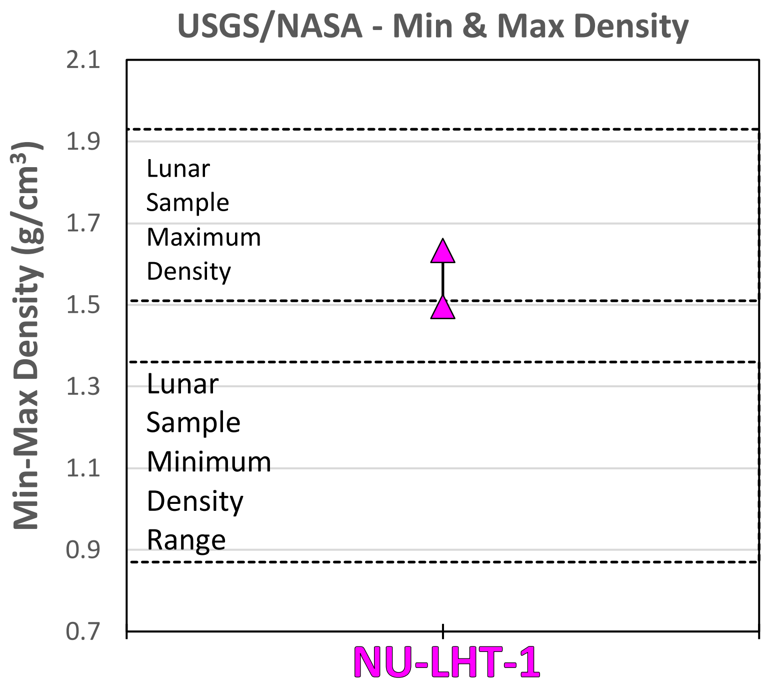

Figure 30: Minimum (bottom triangle) and maximum (top triangle) densities measured for USGS/NASA highland regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Specific Gravity

The specific gravity value measured for the USGS/NASA lunar highland simulant NU-LHT-4M (Table 3) plots within the range measured for various lunar soils (Fig. 31). The NU-LHT-4M highland simulant plots below the recommended typical specific gravity value of Carrier et al. (1991). We note that the NU-LHT-4M simulant has the specific gravity value of 2.89 (Table 3), which is very close to the median specific gravity value of Apollo samples (3.1).

Direct Shear

The cohesion value determined from direct shear measurements for the USGS/NASA highland simulant NU-LHT-4M (Table 4) exceeds the values measured for returned lunar samples (Table 4, Fig. 32). However, the friction angle determined from direct shear measurements for the USGS/NASA highland simulant NU-LHT-4M (Table 4) plots well within the range of values determined for returned lunar samples (Table 4, Fig. 32).

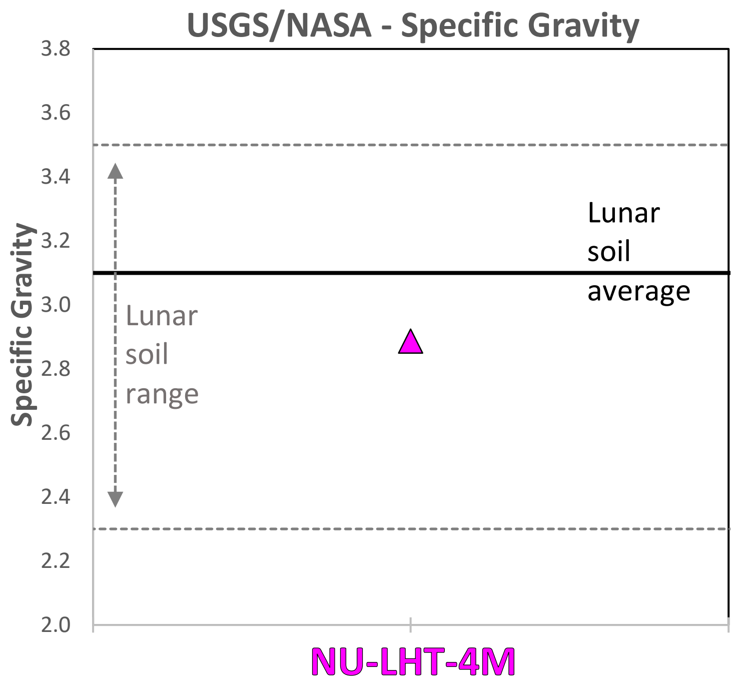

Figure 31: Specific gravity measured for USGS/NASA highland regolith simulant NU-LHT-4M and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

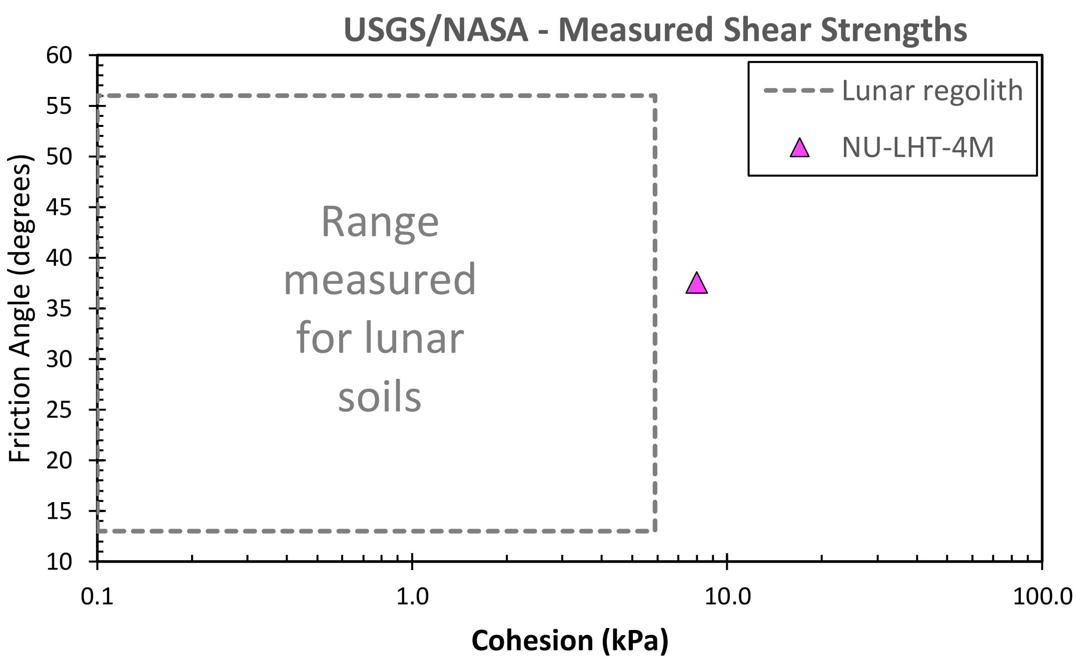

Figure 32: Friction Angles vs. Cohesion determined from direct shear measurements of USGS/NASA highland regolith simulant NU-LHT-4M in this study and lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Supply Chain and Quality Control

The NU-LHT series is not currently in mass production, although the USGS is working with NASA researchers to improve the fidelity of the glass component and are currently considering re-starting its simulant efforts.

COMPARISONS AND EVALUATIONS

Lunar Highland Simulants

Particle Size Distribution: Particle size distribution curves were created from sieved samples to understand the general distribution of particles in highland simulants relative to what was observed for Apollo (Fig. 33). The lunar highland simulants all have fairly good distribution of particle sizes, all plotting within one standard deviation of the average PSD of Apollo soils (Fig. 33). All of the highland simulants provide a good match in the 150-500 micron particle size range; all the simulants contain particles >297 microns (11-25% by weight) suggesting that all feedstocks include some particles >250 micron. All simulants have a steeper PSD slope from 45-150 micron range when compared to the average PSD of Apollo soils (Fig. 33), but still fall within the -1 standard deviation curve. Of the highland simulants examined, OB-1A and OPRH2N plot closest to the Apollo average within the smallest particle size range (<150 microns).

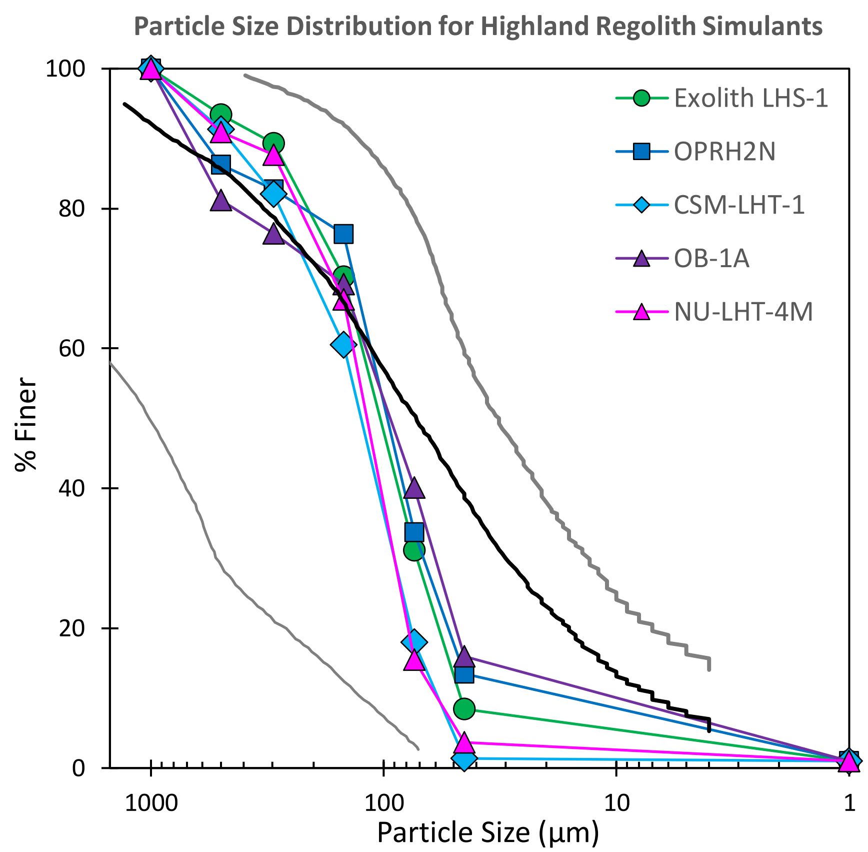

Figure 33: Cumulative particle size distribution of all highland regolith simulants (colored lines) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

Minimum and maximum density: The lunar highland simulants display minimum densities that exceed the range of minimum densities measured for returned lunar samples (0.87-1.36), except for the Off Planet Research highland simulant OPRH2N (1.32). The minimum density for LHS-1 (1.38) just exceeds the upper limit. However, the minimum densities for CSM-LHT-1 (1.43), OB-1A (1.51), and NU-LHT-4M (1.50) plot below or along the lower limit of range of maximum densities measured for the returned lunar samples (Fig. 34). The lunar highland simulants plot within the range of maximum densities measured for returned lunar samples (1.51-1.93), except for the Off Planet Research highland simulant OPRH2N (1.50) that falls just below the lower limit (Fig. 34). In general, the returned lunar samples that have low minimum densities also have low maximum densities (see Table 9.2. of Carrier et al., 1991), but the converse is not necessarily true. In addition, the difference between the minimum and maximum densities for a given sample is more limited for highland simulants (0.18 ± 0.05 g/cm^3) than it is for returned lunar samples (0.67 ± 0.12 g/cm^3). This suggests that the highland regolith simulants contain less porosity when uncompacted than do lunar regolith; furthermore, this lower porosity leads to less compressibility in the regolith simulants when compared to lunar regolith. This characteristic should be considered for experimental work that involves compressing regolith materials.

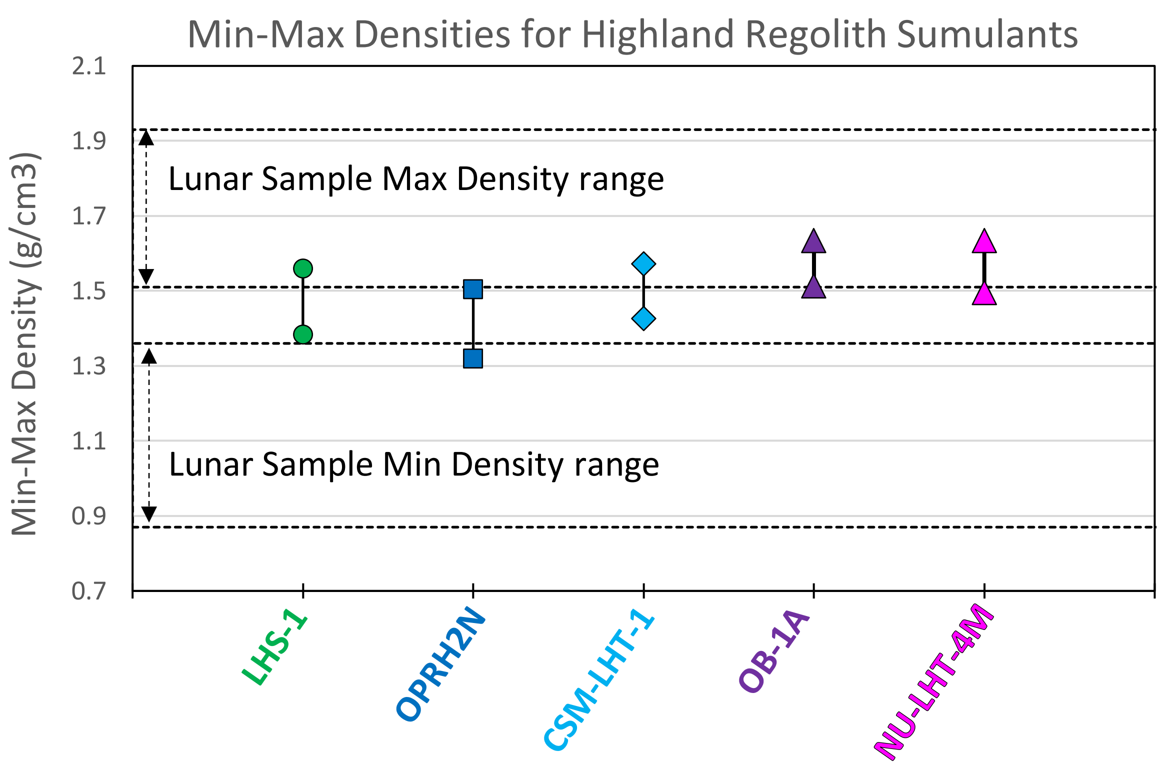

Figure 34: Minimum (bottom symbols) and maximum (top symbols) densities measured for all highland regolith simulants in this study and minimum & maximum density ranges for

Specific Gravity: All of the highland regolith simulants display specific gravity values that fall within the range measured for lunar soils (Fig. 35). Of the highland simulants, OB-1A has the highest specific gravity and plots closest to the average specific gravity value of 3.1 for lunar soils (Fig. 35).

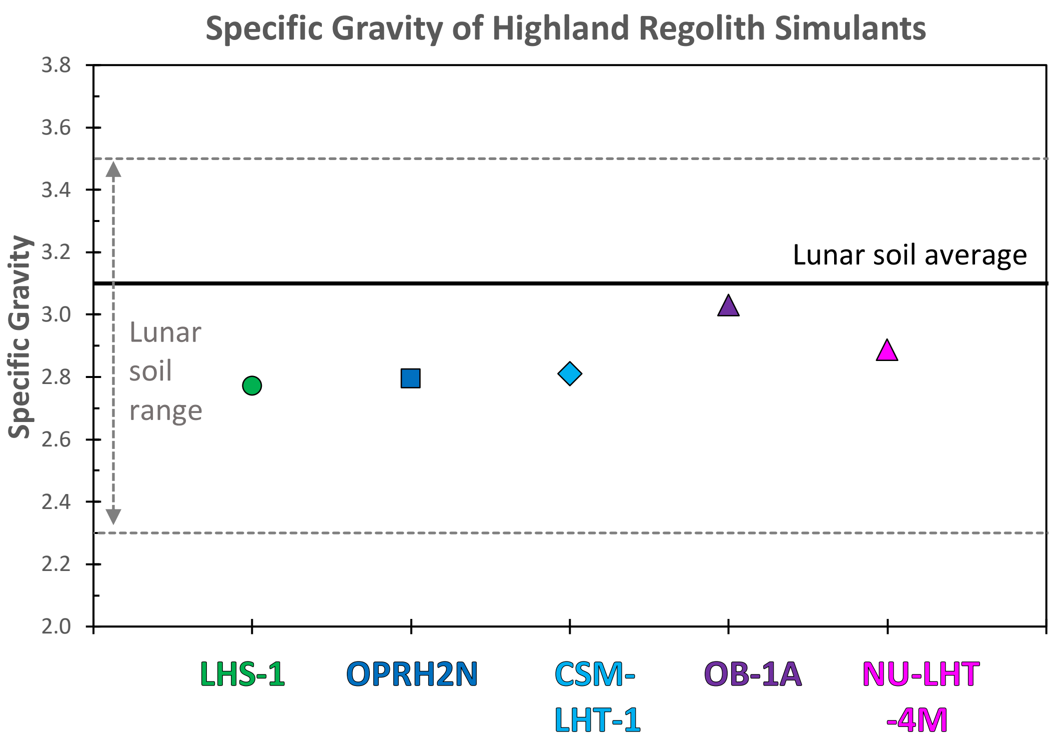

Figure 35: Specific gravity measured for all highland regolith simulant NU-LHT-4M and lunar soil specific gravity average and ranges for lunar samples from various studies summarized by Carrier et al. (1991).

Direct Shear: Direct shear measurements of the highland simulants revealed cohesion values that exceeded the range (0-5.9 kPa) of cohesion values measured for lunar soils (Fig. 36). The closest match to lunar soil cohesion range is the NU-LHT-4M simulant, which has a cohesion value of 8 kPa. The simulant with the most divergent cohesion values is OB-1A (15 kPa). All of the highland simulants plot within the range of friction angles observed for returned lunar samples (Fig. 36), fairly close to the median value.

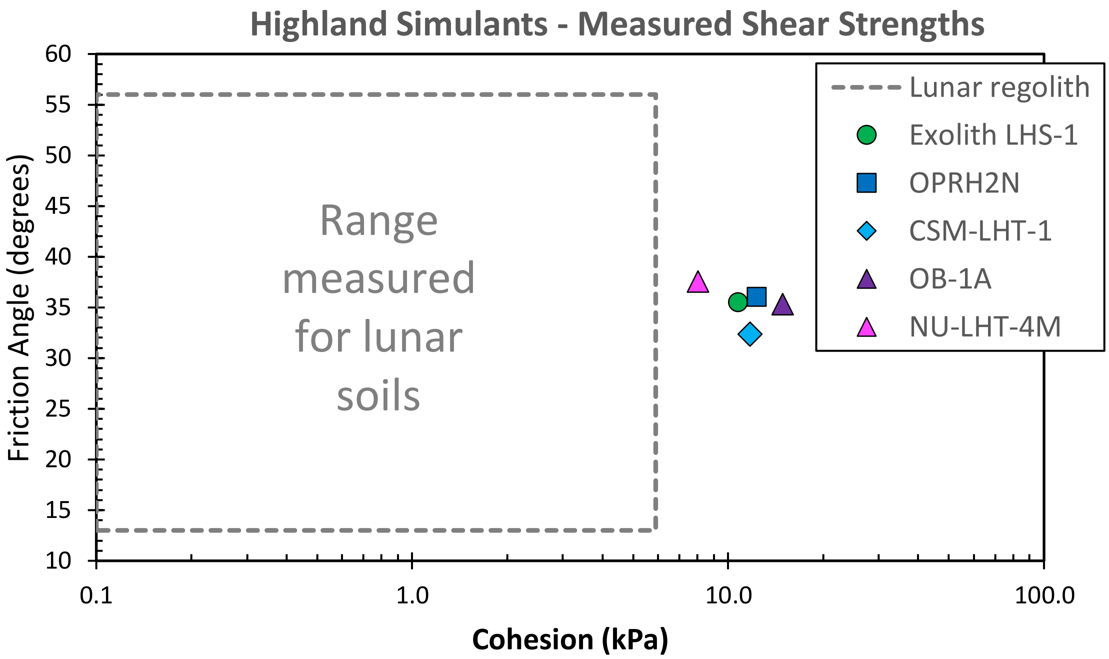

Figure 36: Friction Angles vs. Cohesion determined from direct shear measurements of all highland regolith simulants in this study and lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Lunar Mare Simulants

Particle Size Distribution: Particle size distribution curves were created from sieved samples to understand the distribution of particles in mare simulants relative to what was observed for Apollo (Fig. 37). All mare simulants have a good distribution of particle sizes and plot within one standard deviation of the Apollo soils (Fig. 37), providing a good match in the 150-500 μm particle size range. Furthermore, all the simulants contain particles >297 μm (11-24% by weight), suggesting that all feedstocks include some particles >250 μm. All mare simulants have a steeper PSD slope from 45-150 μm range when compared to the average PSD of Apollo soils (Fig. 37), but still fall within the -1 standard deviation curve. Of the mare simulants examined, OPRL2N plots closest to the Apollo average within the smallest particle size range (<150 μm).

Minimum and maximum density: Figure 38 shows that the lunar mare simulants display minimum densities that exceed the range of minimum densities measured for returned lunar samples (0.87-1.36), except for the Off Planet Research mare simulant OPRL2N (1.31). The minimum density for CSM-LMT-1 (1.50) plots just below the range of maximum densities displayed for lunar regolith (Fig. 38). However, the minimum density for LMS-1 (1.58) plot within

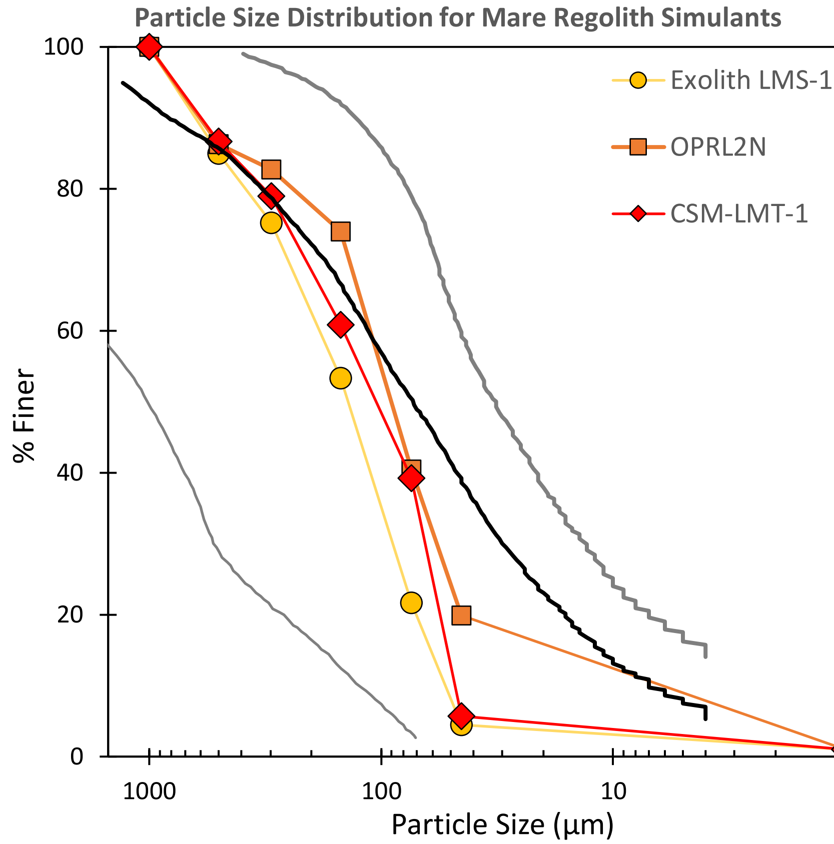

Figure 37: Cumulative particle size distribution of all mare regolith simulants (colored lines) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

the range of maximum densities measured for the returned lunar samples (Fig. 38). Figure 38 shows that the lunar mare simulants display maximum densities plot within the range of maximum densities measured for returned lunar samples (1.51-1.93).

In general, the returned lunar samples that have low minimum densities also have low maximum densities (see Table 9.2. of Carrier et al., 1991), but the converse is not necessarily true. In addition, the difference between the minimum and maximum densities for a given sample is more limited for mare simulants (0.18 ± 0.05 g/cm^3) than it is for returned lunar samples (0.67 ± 0.12 g/cm^3). This suggests that the mare regolith simulants contain less porosity when uncompacted than do lunar regolith; furthermore, this lower porosity leads to less compressibility in the regolith simulants when compared to lunar regolith. This characteristic should be considered for experimental work that involves compressing regolith materials.

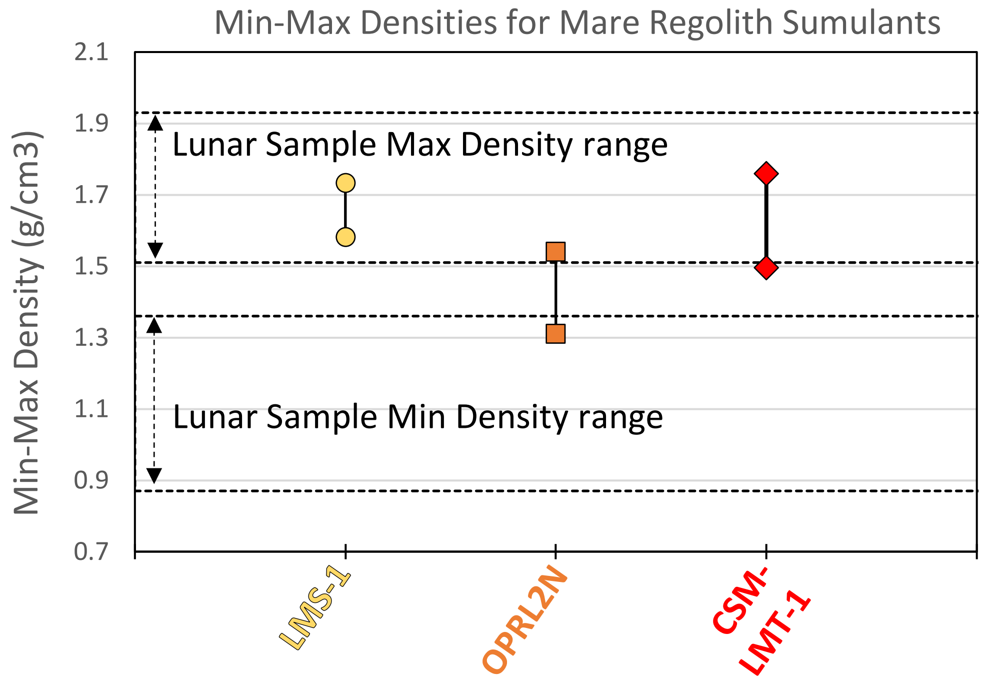

Figure 38: Minimum (bottom symbols) and maximum (top symbols) densities measured for mare regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

Specific Gravity: All of the mare regolith simulants display specific gravity values that fall within the range measured for lunar soils (Fig. 39). Of the highland simulants, Exolith LMS-1 has the highest specific gravity and plots closest to the average specific gravity value of 3.1 for lunar soils (Fig. 39).

Direct Shear: Direct shear measurements of the mare simulants revealed cohesion values that exceeded the range (0-5.9 kPa) of cohesion values measured for lunar soils (Fig. 40, left). The closest match to lunar soil cohesion range is the OPRL2N simulant, which has a cohesion value of 7 kPa. The simulant with the most divergent cohesion values is CSM-LHT-1 (12 kPa). All of the mare simulants plot within the range of friction angles observed for returned lunar samples (Fig. 40, right), fairly close to the median value.

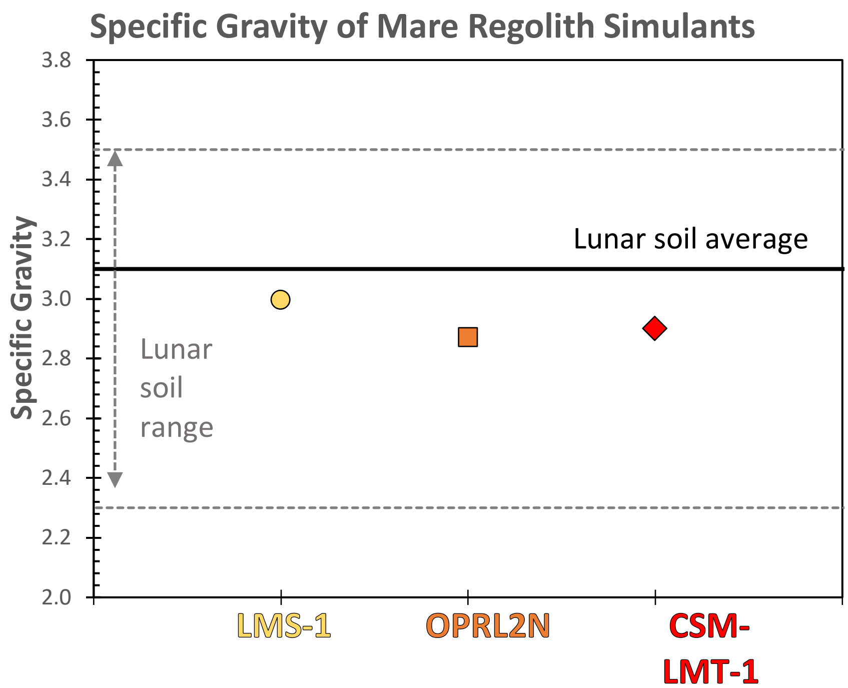

Figure 39: Specific gravity measured for all mare regolith simulants and lunar soil specific gravity average and ranges for lunar samples from various studies summarized by Carrier et al. (1991).

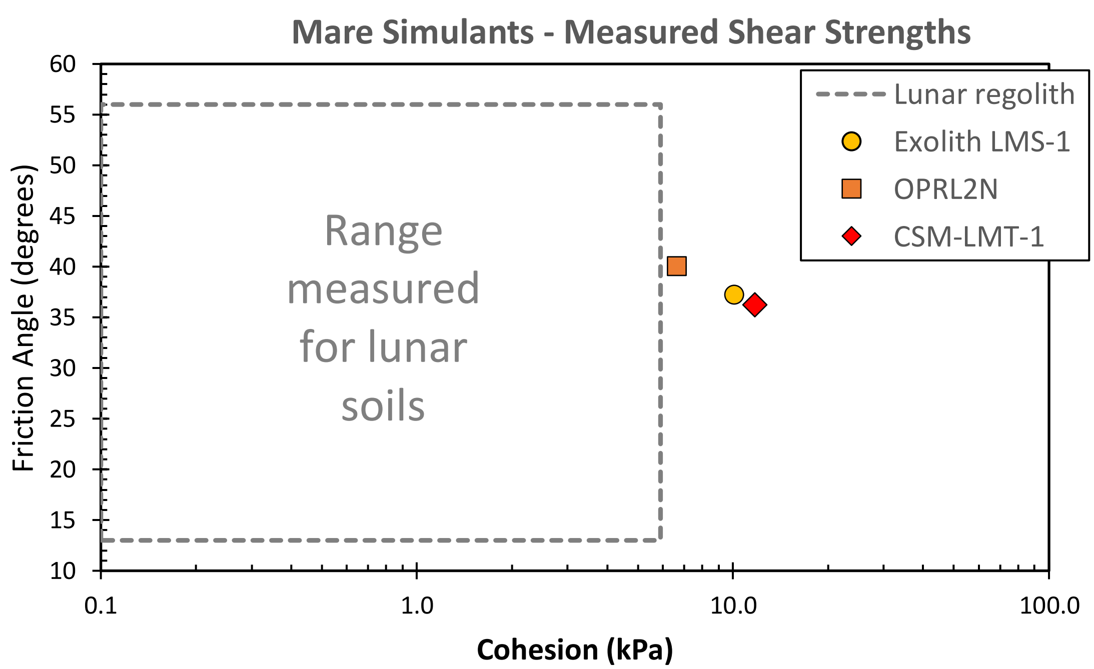

Figure 40: Friction Angles vs. Cohesion determined from direct shear measurements of all mare regolith simulants in this study and lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

Suitability for Testing Technologies

Overall, for the geotechnical properties measured in this study, both highland and mare simulants match the geotechnical properties of lunar regolith. All of the simulants have a particle size distribution that are within 1 standard deviation of the average PSD of Apollo soils (Figs. 21 and 25). However, all simulants tend to have a slightly higher proportion of larger particles, a steeper slope at the intermediate particle sizes (45 – 150 μm), and a lower proportion of the smallest particle sizes. Very similar particle size distributions were observed in previous assessments with generally good matches between the course PSDs derived from sieve analyses and the finer-scale (3 μm) PSDs derived using the Camsizer (Stockstill-Cahill *et al.*, 2021). Matching the PSD of Apollo soils is important because in general soils with larger particle sizes are stronger; therefore, studies should carefully consider how the relatively small differences in PSD of simulants, especially the lower abundance of smaller particles, might impact their results. The close match of simulants particle size distribution to average PSD of Apollo soils should be adequate for most studies.

In terms of density, the simulants all have higher minimum density measurements, except for the simulants from Off Planet Research, which plot at the upper limits of the range displayed by returned lunar samples (Figs. 22 and 26). This indicates that the uncompacted simulants are in general more compacted with less void space between grains than an uncompacted lunar soil. Most of the maximum density measurements plot within the range measured for returned lunar samples (Figs. 22 and 26) except for the OPRH2N highland simulant from Off Planet Research, which plots just below the range. Furthermore, the observation that the simulants display a smaller difference between their minimum density and maximum density (0.18 ± 0.05 g/cm^3) than exists for returned lunar samples (0.67 ± 0.12 g/cm^3) suggests that the simulants undergo less compression under loads than does the lunar regolith. This should be considered for studies that seek to understand how structures will be supported by lunar regolith and how much compaction must take place to create a stable surface.

The specific gravities of simulants provide a good match to the range of specific gravity values that have been measured for lunar regolith. This suggests that the simulants contain similar particle types and porosities measured for lunar regolith, at least within the laboratory setting. Specific gravity is related to voids between grains and within grains and we note that for tests completed under ambient conditions on Earth, the inter-grain void space will be filled with air, which differs from what would be measured under vacuum or at the lunar surface. Therefore, the stability of lunar soils may differ on the Moon from what is observed on Earth. In fact, there is evidence that the stability of the upper 20 cm differs from the subsurface (Carrier et al., 1991;

Lucas et al., 2022), so testing should consider stratification of lunar soils and simulants in terms of density, specific gravity, and related geotechnical profiles.

Finally, shear strength measurements revealed very different behavior in the cohesion of simulants relative to lunar regolith, specifically that the simulants display higher levels of cohesion than returned samples. However, the frictional angles of simulants provided an excellent match to the frictional angles measured for returned lunar soils.

Furthermore, it should be noted that even lunar regolith behaves differently on Earth than it does *in situ* on the lunar surface. Carrier et al. (1991) noted that lunar regolith had different shear strength behavior *in situ* at the lunar surface relative to laboratory measurements. Looking the Apollo and Surveyor best estimates, we do see much steeper friction angles than derived for returned lunar samples. In fact, Carrier et al. (1991) suggested that under the reduced stresses present on the lunar surface (1/6 gravity), the irregular and reentrant soil particles tend to interlock, increasing the shear strength of lunar regolith *in situ*. Given all this information, careful consideration should be given to technological development involving load bearing capacity.

CONCLUSIONS

As has been reiterated numerous times (e.g., Simulant Working Group, 2010; ISECG Dust Mitigation Gap Assessment Team, 2016; Taylor et al., 2016), the evaluation of a simulant is specific to its application. For ISRU applications, it has not yet been demonstrated that minor components of lunar soils (e.g., nanophase iron metal) or even major components (agglutinates) are a critical property that simulants must replicate. However, the specifics of a particular application or test may involve details for which such components are critical and agglutinates do have implications for the geotechnical properties of a soil. The LEAG–CAPTEM Simulant Working Group (2010) "strongly recommended that simulant users consult with a lunar geologist or lunar scientist prior to ordering or using simulants." We agree with this recommendation, and our initial conclusions point to simulants which provide general fidelity to geotechnical properties (dependent on factors that include particle size distribution, particle shape, agglutinates) and composition (mineralogically and chemically) that are likely to meet the needs of most, but certainly not all users.

We emphasize that lunar regolith and simulants will not behave in the same way on Earth as they would on the Moon. Due to the lack of an atmosphere to protect the lunar surface, volatile constituents are implanted in the surface of the grains by the solar wind, which are not present naturally in the simulants. Similarly, the solar wind and cosmic rays "activate" the surfaces of regolith grains through excitation or removal of electrons or disruption of crystal lattices, and these activated particles may stick more strongly together through adhesive or cohesive forces (e.g., ISECG Dust Mitigation Gap Assessment Team, 2016) as well as bind more strongly with volatiles (Bennett et al., 2013). None of these simulants reproduce the nanophase iron found in lunar grain rims which gives the regolith magnetic properties. In addition, the lower lunar gravity results in lower confining stresses, which will also change the properties of regolith relative to terrestrial studies, including shear strength behavior and frictional angles (Carrier et al., 1991; Sture et al., 2004). As lunar surface technologies progress, there should be ongoing coordinated analyses on the effects of these distinctive properties on the test and demonstration results.

Despite the caveats, it is likely that simulants from current simulant providers could meet the needs of most users. These providers have worked to develop simulants that provide fidelity to lunar soils in terms of composition, particle size morphology, and have the flexibility to adapt to user needs for a site-dependent composition. This work shows that many of the simulants are fairly close matches in terms of geotechnical properties to returned lunar soils. Where simulants are lacking, there is no easy remedy. For example, one of the major differences in composition is the more sodic plagioclase in the simulants. However, large deposits of anorthite with An-numbers as high as lunar samples do not exist on Earth. Producing nanophase iron in simulants in large quantities is difficult. Producing simulants with the correct activation state would be extremely difficult if not impossible. Thus, we include these not as discriminators amongst the various simulants, but as reminders that no simulant achieves these qualities that some researchers have deemed important to ISRU testing.

For advanced (high TRL) testing related to ISRU needs, it may be wise to compare results using a simulant with and without agglutinates, and potentially even a lunar soil. One lunar sample in particular, 70050, a 2.2 kg mixture of soils from across the Apollo 17 landing site, has been identified as ideal for engineering tests because it lacks the detailed provenance that would make it more useful for scientific studies (Taylor et al., 2016). Apollo Sample Curator Dr. Ryan Zeigler notes several ISRU and instrument development projects have successfully proposed to CAPTEM for the use of Apollo samples. However, for low TRL studies, the basic mare and highland simulants from the providers outlined here, excluding agglutinates, are likely sufficient.

Given the similarities between simulants, a choice between these suppliers may come down to availability (supply chain), consistency, quality control, and cost. All the companies are likely to be able to meet supply chain needs with sufficient notice. Seasonal dependence on mining anorthosite can be mitigated by advanced planning and using alternate anorthosite sources, such as the White Mountain anorthosite (Gruener et al., 2020), of which a large quantity has already been mined from Greenland and stored in South Carolina. Exolith is expanding their quality control process and have attempted to create a website with greater transparency regarding their simulants. Off Planet Research does employ rigorous quality control, including analysis of particle size and chemistry. Colorado School of Mines strives to provide high fidelity simulants that are well validated, so each batch will be evaluated to make sure that they are within the "tolerance range" for composition and particle size. Both the OB-1A and NU-LHT- series simulants are not currently under production so it is not known what quality control processes would be included should their production be renewed; however, most previous batches are well documented in terms of their composition and geotechnical properties. Additional verification and testing of simulants prior to delivery is possible for most providers, but this will increase the cost and require additional time before delivery.

ACKNOWLEDGEMENTS

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