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).

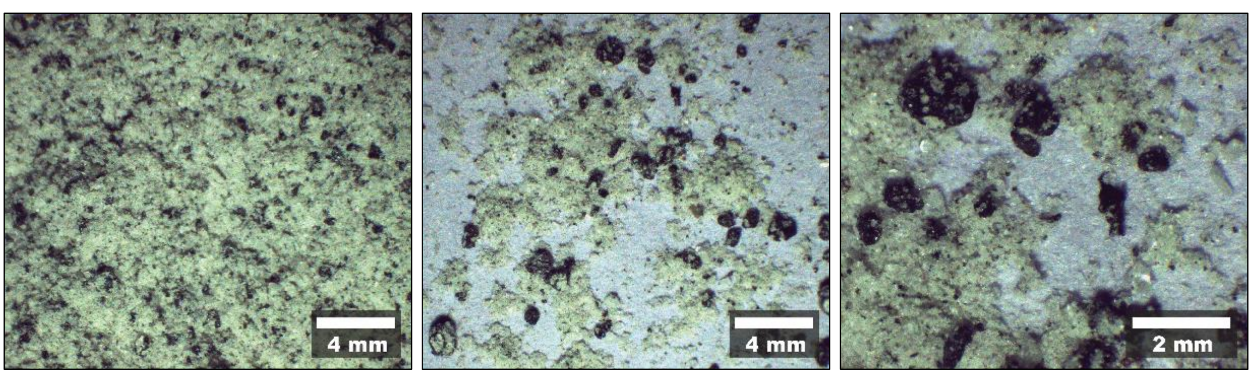

Figure 5: Microscopic images of unsieved Exolith LHS-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of LHS-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of LHS-1 simulant dispersed onto weighing paper for clarity. **(Right)** Higher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

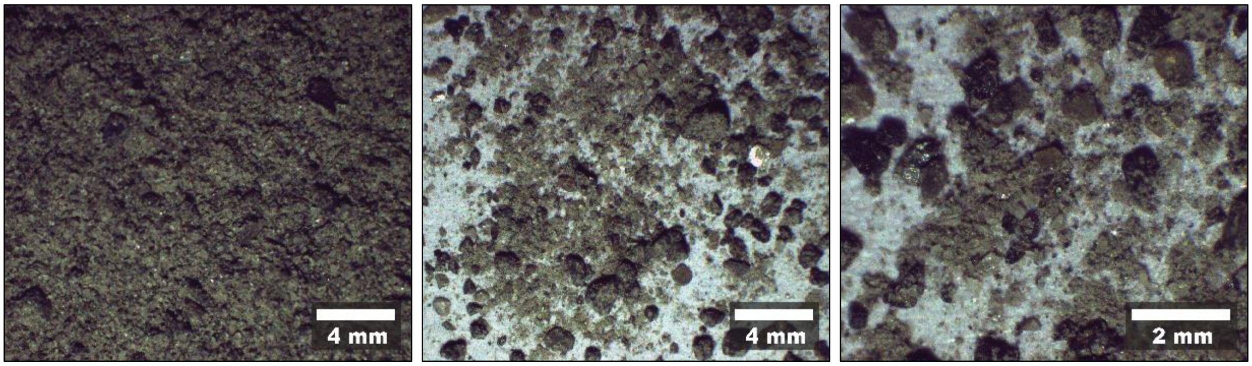

Figure 6: Microscopic images of unsieved Exolith LMS-1 simulant used for testing. **(Left)** Low magnification (0.75x) overview image of LMS-1 bulk simulant. **(Middle)** Low magnification (0.75x) image of a small amount of LMS-1 bulk simulant dispersed onto weighing paper for clarity. **(Right)** Higher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

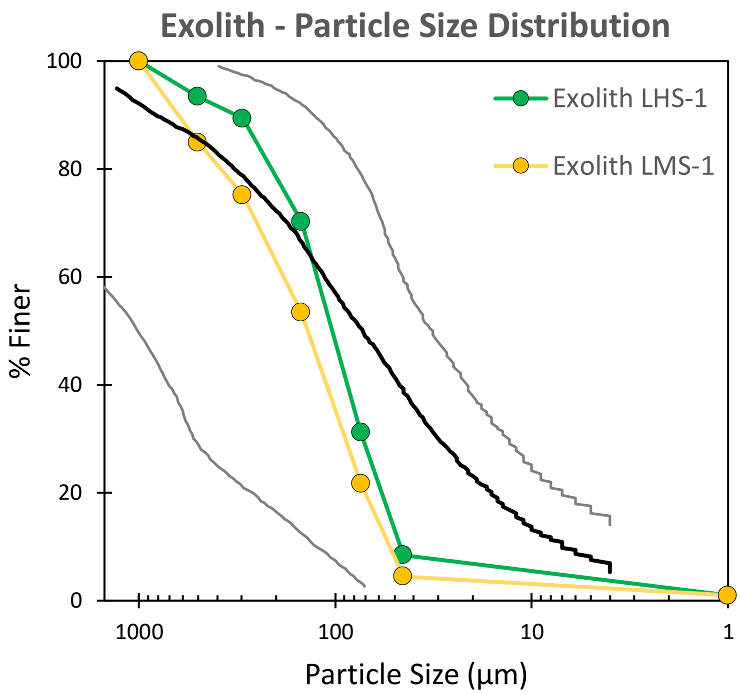

Figure 7: Cumulative particle size distribution of Exolith simulants (green and yellow) in comparison to Apollo average PSD (black) and ±1 standard deviation (gray).

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.

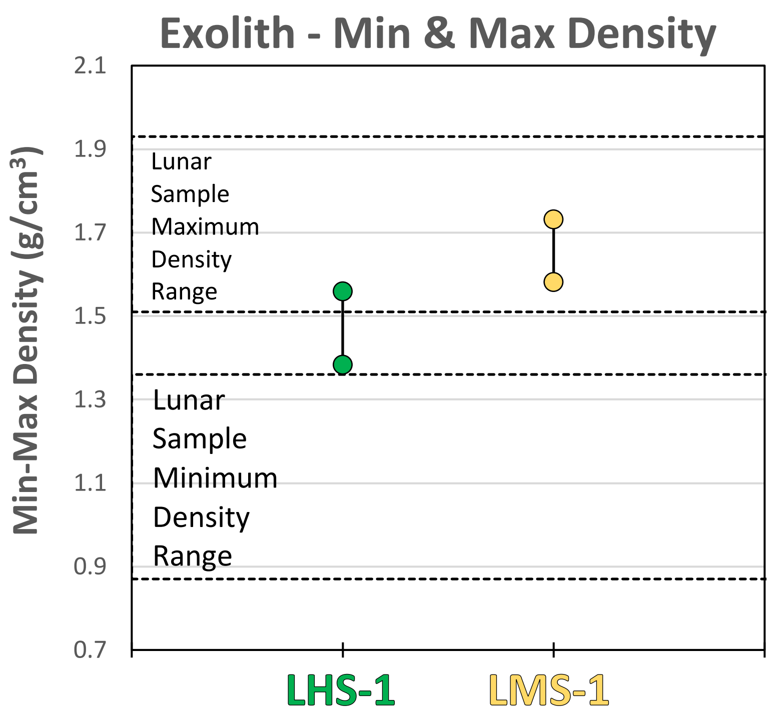

Figure 8: Minimum (bottom circles) and maximum (top circles) densities measured for Exolith regolith simulants in this study and minimum & maximum density ranges for lunar samples from various studies (Table 2).

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.

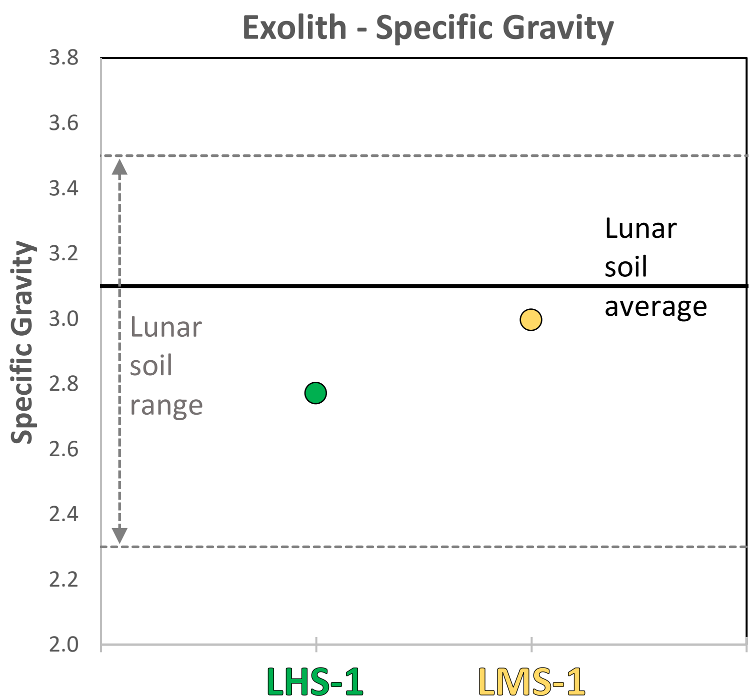

Figure 9: Specific gravities measured for Exolith regolith simulants in this study and lunar soil specific gravity average and the average and range of specific gravities measured for lunar soils from various studies, as summarized by Carrier et al. (1991).

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).

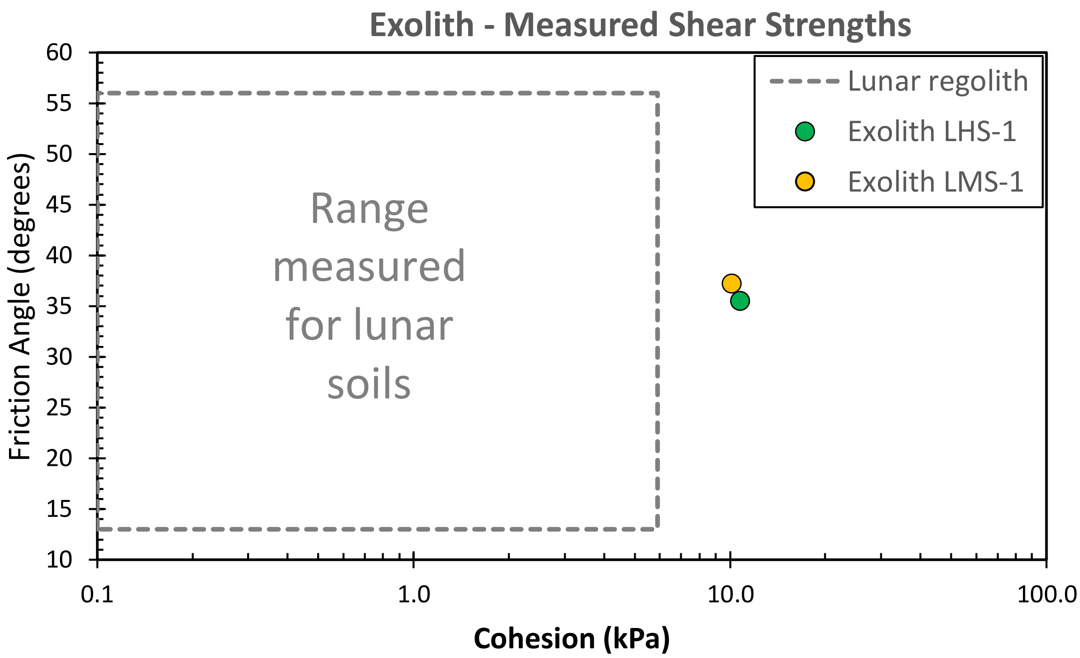

Figure 10: Friction Angles vs. Cohesion determined from direct shear measurements of Exolith regolith simulants in this study and the range of lunar soil values for lunar samples from various studies summarized by Carrier et al. (1991).

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.