Lunar Surface Innovation
CONSORTIUM

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

JHU-APL LSII REPORT:

2021 Lunar Simulant Assessment

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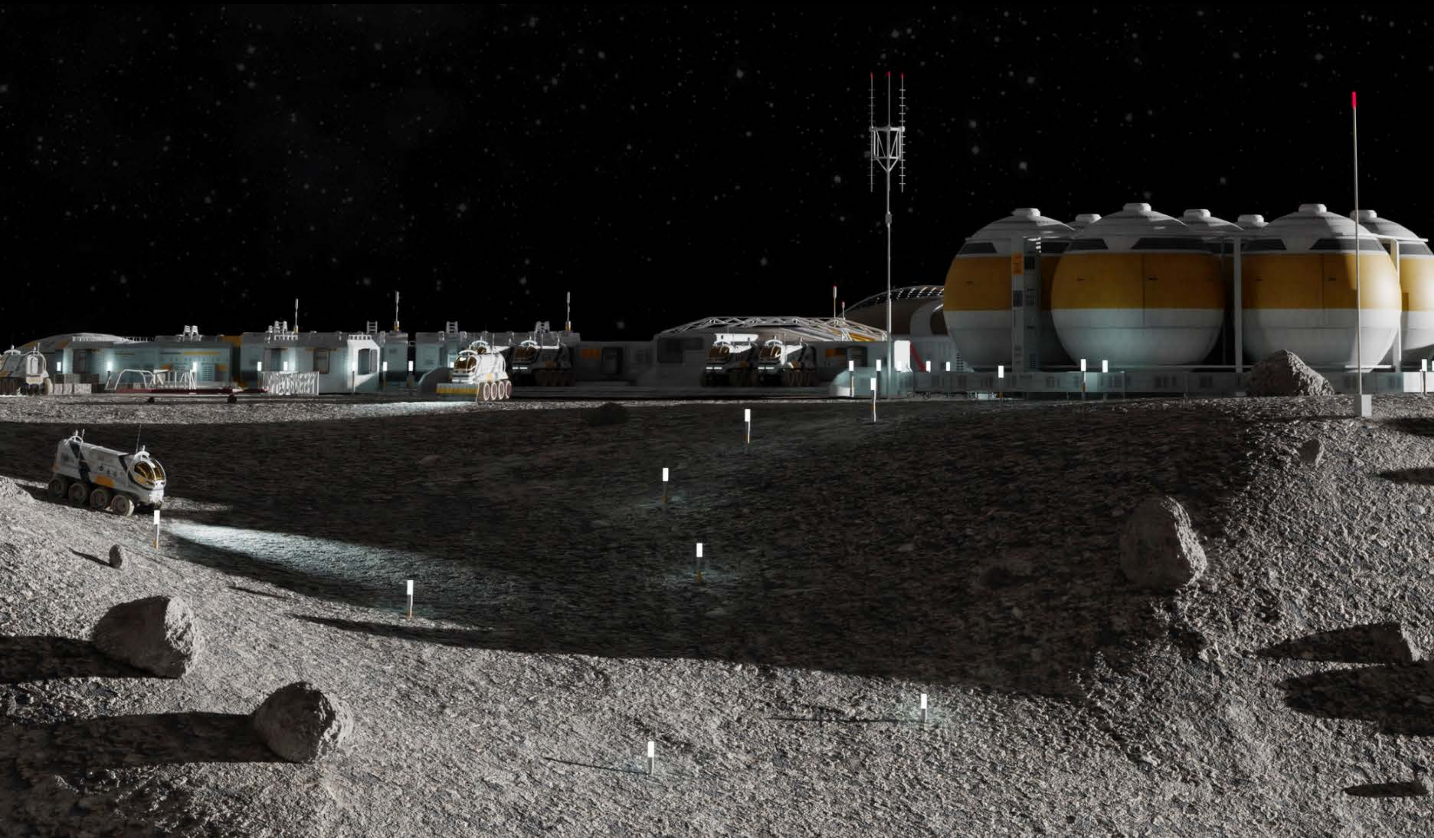

EXECUTIVE SUMMARY

This assessment contains evaluations of lunar regolith simulants that are commercially-available in 2021. It provides an update from the 2020 Lunar Simulant Assessment published by the JHU-APL LSII team in late January of 2020. This update includes simulants that were previously evaluated (Exolith Labs LHS-1 and LMS-1; Off Planet Research OPRH3N and OPRL2N; Outward Technology LHA-1 and LMA-1) because these simulant providers stated they have undergone significant changes to either process or feedstock used to produce these simulants. Re-assessing these simulants annually will also allow us to constrain batch-to-batch variations in the characteristics of the simulants. In addition, this document assessed lunar simulants from a new lunar regolith simulant provider at the Colorado School of Mines (LHT-1 and LMT-1).

The main section of this document provides information regarding each simulant provider, their available simulants, comparison of the evaluated simulant characteristics (e.g., particle size and shape, composition, etc.) to Apollo samples, and details regarding supply chain and quality control. All four providers shared information and sent simulant for this evaluation. Overall, small changes to the processing in the last year has produced improvements in the simulants available for various applications. As detailed in this document, the highland and mare simulants all exhibit a particle size distribution within one standard deviation of an average Apollo regolith. Furthermore, the particle shapes of all simulants are more rounded and less complex than Apollo regolith grains. The agglutinate simulants produced by Outward Technology show strong improvement in their overall similarity to Apollo agglutinates relative to samples assessed previously. Compositionally, all the simulants provide a fairly good match to lunar regolith, although all simulants are more sodic than Apollo regolith. This is due to the fact that terrestrial plagioclase contains more sodium than lunar plagioclase. For most applications, these differences from Apollo 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.

Methods used for this evaluation included sieving the samples into six particle size fractions and weighing these fractions to determine a rough particle size distribution (PSD) by weight. In addition, grains were characterized for size and shape of the particles in the lunar regolith simulant samples using the Camsizer X2. Particle characteristics were compared to similar data collected for Apollo regolith samples. The composition of the simulants were determined by various methods. First, we examined polished epoxy mounts of the 125-250 μm particle size fraction for each simulant using a Hitatchi TM 3000 tabletop Scanning Electron Microscope (SEM). Elemental maps were produced using the associated Bruker Q70+ silicon drift detector energy dispersive spectrometer (EDS) system. In addition, we examined bulk simulant powders using X-ray Fluorescence (XRF) to derive bulk elemental composition and X-ray Diffraction (XRD) to determine the number and rough amounts of crystalline mineral phases present in the sample.

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INTRODUCTION

LEAG and CAPTEM released a 2010 report that detailed 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 iterations. In 2020, the APL Lunar Surface Innovation Initiative presented an initial assessment of six lunar regolith simulants from the new generation, including reporting new analyses and evaluation of their potential suitability for specific uses. Here, we provide an updated assessment of eight available lunar simulants, including new 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.

Relatively little work has been published on the shapes of particles in actual lunar regolith. Carrier et al. (1991) compiled shape information on lunar soil grains from papers by Gorz et al. (1971, 1972). These data were derived from shape analysis performed on (Scanning Electron Microscope) SEM images. Image processing was used to determine the aspect ratio of a best-fit ellipse (Fig. 1) and a parameter that they call "complexity", which is equal to the ratio of the actual measured particle perimeter to the perimeter of the best-fit ellipse. The Gorz analysis was done on the smaller end of the soil size distribution (< 30 µm for Apollo 14 and 15 soils; <6 µm for an Apollo 12 soil).

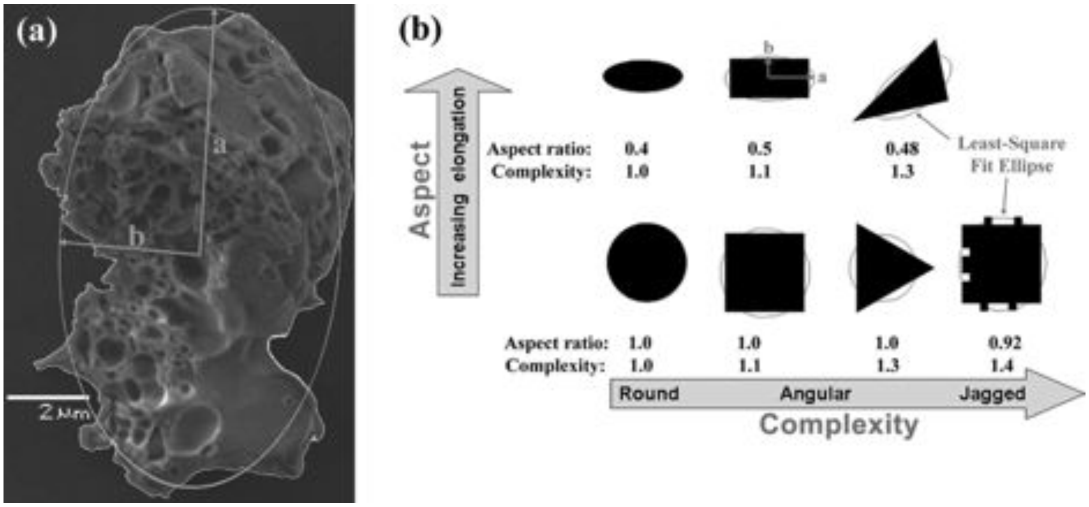


Figure 1: Illustration of the parameters "aspect" and "complexity" employed by Liu et al. (2008), their Figure 1 shown here.

Another particle shape study is that by Liu *et al.* (2008), who examined five Apollo lunar soils and the fine fraction of JSC-1A simulant. These workers were primarily interested in dust toxicity, and hence looked at finer sieve fractions (< 43 µm for 100084 and 70051, < 10 µm for 12001, 15041, 79221, and < 20 µm for the "JSC-1Avf" simulant). Liu et al. (2008) measured the aspect ratio and complexity on SEM images and found that the frequency distribution of aspect ratios for all the lunar samples measured peaked at aspect ratio values of ~0.7. Unfortunately the Liu *et al.* (2008) data is presented as histograms that preclude extraction of quantitative values from their figures.

Work conducted at Marshall Space Flight Center a decade ago analyzed the shape characteristics of six lunar regolith simulants available at that time. Rather than summarize those findings or perform comparisons with the simulants that are the subject of the present study, we simply refer the interested reader to Rickman et al. (2012).

Summary of changes since the 2020 Assessment**:** In order to extend and improve the 2020 assessment, we've made several changes to our methods and simulants evaluated. We added two analyses to better assess the compositional information of the simulants. We added X-ray Fluorescence (XRF) of the bulk samples to get many of the major elements abundances of the simulant materials. XRF allows us to assess the composition of larger quantities of materials to generate a more accurate portrayal of the bulk composition. We also used X-ray diffraction (XRD) to produce semi-quantitative mineralogy/phase identification of the bulk simulants. XRD allows identification of the major crystalline phases present in the samples with an approximate abundance of each phase within the sample. Both of these are complimentary to the compositional maps collected using a scanning electron microscope (SEM) with Bruker Q70+ silicon drift detector energy dispersive spectrometer (EDS) system for the 125-250 μm particle size split of each simulant. Indeed, XRF, XRD, and SEM compositional maps are used in tandem to better understand the simulant compositions. Furthermore, we have added highland and mare simulants from a new provider at the Colorado School of Mines. We hope this additional information will provide simulant users with a complete picture of simulant options and suitability for their applications and experiments.

METHODOLOGY

We obtained lunar regolith simulants from four simulant providers including Exolith Laboratories, Off Planet Research, Colorado School of Mines, and Outward Technologies. Simulants from three of these providers (Exolith, Off Planet Research, Outward Technologies) were evaluated in 2020, but the simulants were evaluated again this year due to significant changes in source or processes that could influence our assessment.

We dry sieved each lunar regolith simulant sample into six particle size fractions: <45 µm, 45–75 µm, 75–125 µm, 125–250 µm, 250–500 µm, and >500 µm. We completed the dry sieving in a similar approach to analyses of some Apollo samples. We quantified the particle size–frequency distribution for each soil by determining the mass of each sieved size fraction. We then calculated the cumulative particle size mass for a given size fraction, which is the mass of the size fraction plus the mass of all smaller size fractions and plotted the cumulative particle size mass data against particle size for comparison to Apollo regolith samples. Next, we washed the 125–250 µm size fraction with ethanol to remove clinging fine particles for remaining analyses. Finally, we assessed each simulant's particle morphology and visual similarity relative to types of lunar regolith for three size fractions (75–725 µm, 125–250 µm, >500 µm) using a binocular microscope.

We mounted simulant samples by encasing loose regolith simulant grains from the 125-250 µm size split within epoxy and polished the rounds with a fine polish to use with the scanning electron microscope (SEM) at the JHU Applied Physics Laboratory. The SEM work was done using a Hitatchi TM 3000 tabletop SEM, which produces sample images at 15x–30,000x magnification. We used the Bruker Q70+ silicon drift detector energy dispersive spectrometer (EDS) system outfitted on the tabletop SEM to measure elemental composition and produce elemental maps. Elemental information allows us calculate oxide abundances for comparison to bulk rock compositions of Apollo samples. We note that a similar geochemistry does not necessarily imply similar mineralogy, due to the very differing oxidation states of the Earth and the Moon.

Size and shape of the particles in the lunar regolith simulant samples were also characterized using the Camsizer X2, an instrument built by Retsch Technology. The Camsizer X2 operates by entraining a sample of granular material into a stream of air, which separates particles that are clinging together. The particles pass in front of a microscope outfitted with a high-speed camera. The images are analyzed with built-in image-processing algorithms to extract size and shape parameters for each grain. The software creates a velocity profile of the particles and applies a correction to the measurement, in order to ensure that particles are not measured more than once. For each sample, we measured three different aliquots (of ~100 mg each) of the bulk sample and averaged the results. The particle size (xc min) is assigned to be the smallest of all maximum chords of the particle projection. We used a bin size of 3 µm for all samples (i.e., 0-3 µm, 3-6 µm, etc.). A sense of the size distribution of the particles is provided by the values of D(10), D(50), and D(90), which represent the volume percent of particles below the specified particle diameter. For example, a value of D(50) = 75 µm indicates that 50% of the particles are less than 75 µm in diameter. Assuming a constant grain density for particles across the size bins, the volume percent as measured optically by the Camsizer should be equivalent to weight percent derived from sieve analysis.

The Camsizer system reports several shape parameters for each bin size, including:

- Aspect ratio (*i.e.*, short axis/long axis; a spherical particle has aspect ratio = 1, more elongated particles have progressively smaller values).
- Sphericity (*i.e.,* spht = $(4 \times \pi \times A)/(P^2)$, where P is the measured perimeter of a particle projection and A is the projected area of the particle. For a sphere, spht = 1.

Although a rigorous comparison has not been performed, the "complexity" parameter may gauge shape properties in a manner similar to the sphericity metric computed by our Camsizer instrument.

Bulk sample elemental composition was derived from X-ray Fluorescence (XRF), a non-destructive characterization technique used for the chemical analysis of materials that involves the exposure of samples to high energy X-rays and detection of released characteristic electrons from atomic K and L orbital shells. For the lunar regolith simulants, we used a portable Thermo Scientific Niton XL3t 980 analyzer. The system is equipped with a 50 kV x-ray tube with an Au anode and a thermoelectrically cooled large area drift detector. All measurements were conducted with the analyzer in a bench-top test stand that facilitated sample loading and minimal contribution from surroundings. Samples were taken from simulant vials and placed on high transmission thin polycarbonate films of same diameter as the XL3t gun aperture. To address lot-to-lot variability and grain size dependent composition, samples collected were intentionally small, carefully located in the center of the polycarbonate circular films. All measurements were performed for five splits. Measurements were collected in open collimator mode (8 mm spot size) using the Mining Mode setting for major constituent composition determination, reported in percentage by weight (% wt). A balance value was returned for elemental constituents not detectable in this mode. Three excitation filters were used for the selective detection of elemental energy lines in the main (6 – 50 keV), low (2 – 15 keV), and light (< 8 keV) spectral energy ranges. Filters were set to 20 seconds test times for a total sample scan time of 60 seconds. Sample analysis is automatically performed by the Niton Data Transfer (NDT) software suite. For very light elements, such as Mg and Na, fluorescence signal is limited by poor x-ray absorption and interference. For Mg, the NDT software reports Mg compositions with a “below the limit of detection” flag, but provided values at or above the expected detection limits. For Na, the portable XRF is unable to detect x-ray lines. As such, XRF measurements were combined with SEM compositional analysis of 125-250 um size splits to derive the average values for Na_2O.

Finally, semi-quantitative mineralogy/phase identification was done using both x-ray diffraction (XRD) and SEM elemental maps. XRD is a rapid analytical technique used to identify a crystalline material by examining how incident x-rays are diffracted from a crystalline material. The resulting diffraction peaks are characteristic of the material’s crystal structure and can therefore be used to identify the mineral phases. We note that XRD does not typically detect glassy or amorphous phases present within a sample and quantifying the phases is further complicated when many low-symmetry phases are present in a sample. We used a Panalytical Empyrean diffraction cabinet to collect the diffraction patterns and determined the number and rough amount of phases present by the Reference Intensity Ratio method. For samples with multiple phases, the results are considered semi-quantitative values since no standards were mixed in with the regolith simulants and no refinements were performed on the patterns. Phase abundances were also derived from SEM elemental maps for comparison to the XRD results since SEM analyses are agnostic to the crystalline nature of the material being analyzed. This allowed us to distinguish phases (e.g., plagioclase vs. glassy mafic phases) to estimate relative abundances in the 125-250 μm size split. We note that the mineral abundance of a given size split may differ from the bulk sample, but the information can be useful for placing the XRD results in context.

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 four 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; she has participated in science research for 4 years and brings 9 years of experience in business management.

Exolith also offers complimentary consulting on simulant-related science to assist in the choice and use of 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.

Available Simulants

The Exolith lab makes a range of simulants for asteroids (CI, CM, and CR simulants), Mars (MGS-1, MGS-1S, MGS-1C, and JEZ-1), and the Moon (lunar highland simulant LHS-1 and lunar mare simulant 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.

Since the previous assessment, the source components used to create their lunar simulants have changed. Previously, the anorthosite component was derived from the Stillwater Anorthosite; Exolith now uses White Mountain Anorthosite (aka GreenSpar) from Hudson Resources, Inc. This component was changed to improve chemical fidelity and supply chain quantities. In addition, they have 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 still being researched by the Exolith team because the commercial company has been reluctant to reveal the source mine. Detailed analyses (XRD and XRF) of source components are provided in their report entitled "Exolith Simulants Constituents Report" available on their website. Since there were significant changes to the source components used for both simulants, we will provide a new assessment of the Exolith lunar regolith simulants.

The Exolith lunar highland simulant LHS-1 (Fig. 2) is primarily composed of anorthite (74.4 wt.%) that was mined from the White Mountain Anorthosite (or GreenSpar) from Kangerlussuaq, Greenland. The GreenSpar anorthosite has a plagioclase content of 82–94 wt% with an average An# of 83 (Gruener *et al*., 2020). The glass that makes up 24.7 wt.% of the LHS-1 simulant 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.

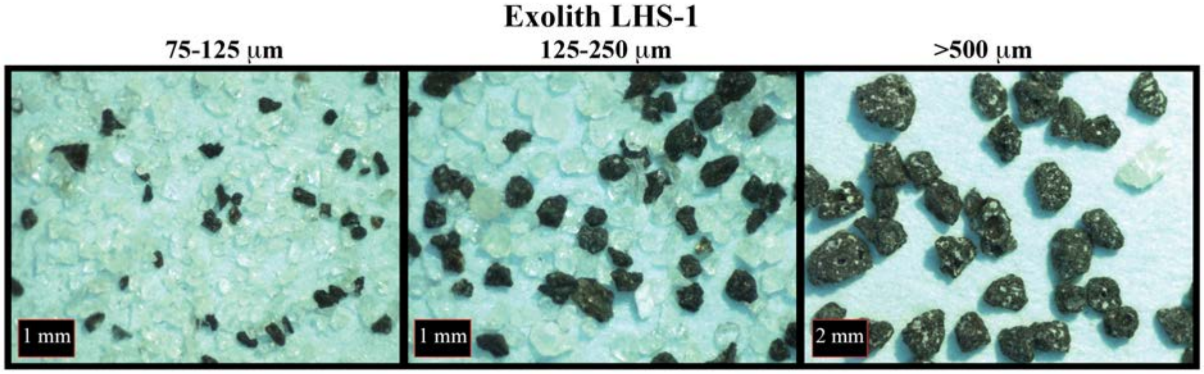


Figure 2: Exolith Lunar Highland Simulant (LHS-1), shown at three different size fractions. The light particles are largely anorthosite and the dark particles are mainly basaltic glass.

The Exolith lunar mare simulant LMS-1 (Fig. 3) is intended to be representative of low- to moderate-titanium (in this case, 7.3 wt% TiO_2) mare. 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.

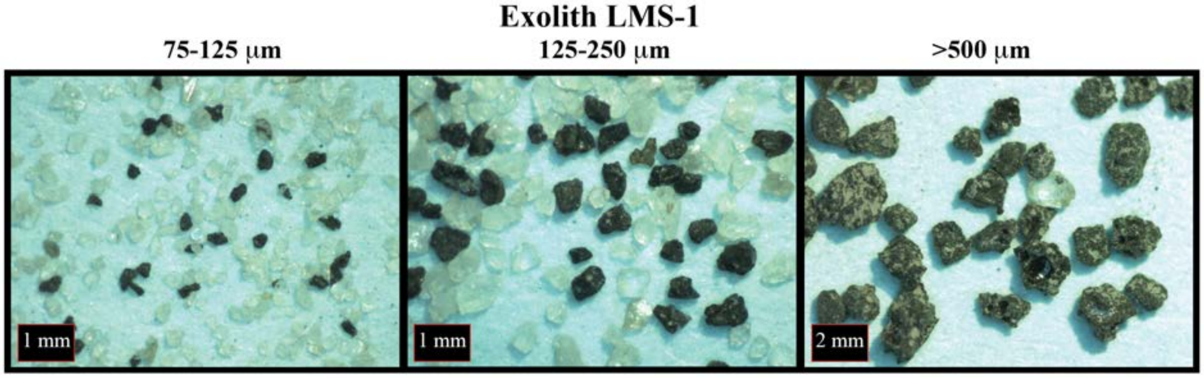


Figure 3: Exolith Lunar Mare Simulant (LMS-1), shown at three different size fractions. LMS-1 consists of a mix of mineral and lithic fragments.

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 um. 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.

Finally, Exolith 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%

anorthosite agglutinates by weight. The anorthosite agglutinate can also be purchased separately to mix into a simulant. Exolith simulants do not include nanophase iron.

Particle Morphology

Table 1 provides a comparison of the aspect ratio data for lunar soils (Liu *et al*., 2008; Carrier *et al*., 1991; Gorz *et al*., 1971; 1972) and the aspect ratio medians from our analysis of the lunar simulants. The aspect ratio values that we determined for the four regolith simulants shown in Table 1 are very similar (~0.74) and correspond to a low to moderate degree of elongation. The aspect ratio value for the simulants slightly exceed the modal values of ~0.7 that were reported by Liu et al. (2008) for Apollo soils 10084, 12001, 15041, 70051, and 79221. Table 1 reports lunar soil particle data for a different set of Apollo samples, from Gorz et al. (1971, 1972) as compiled by Carrier et al. (1991). The Gorz data appear to indicate a somewhat greater elongation (lower aspect ratios) than those found by Liu et al. (2008) and for our measurements of the lunar simulants. It should be noted that the available shape data for the Apollo soils is for the lower end of the size range (<30 µm), whereas the simulant data are for the entire <900 µm fraction.

Although basaltic glass is included in the Exolith lunar simulants, the glass is a not good analog for agglutinates or lunar pyroclastic glasses in terms of particle shape. Agglutinates are highly irregular, and consist of only ~35% glass on average, with the remaining volume made up of local loosely welded mineral and lithic fragments. Pyroclastic glasses are spherical particles with a mean grain size of ~45 µm (Lucey et al., 2006). The basaltic glass used in the Exolith simulants is crushed from larger particles, and thus similar in shape to the other grains in the simulant.

Table 1: Aspect ratio data for Apollo soils and lunar simulants.

Sample	Size fraction (µm)	Aspect ratio mode*	Aspect ratio median+
14163 Non-mare	1.2 – 30	0.6 – 0.7	
Exolith LHS-1 Highland	0-900		0.740 ± 0.004
Off Planet OPRH3N Highland	0-900		0.698 ± 0.004
CSM-LHT-1 Highland	0-900		0.719 ± 0.003
12001 Mare	3.2 – 6.1	0.3 – 0.4	
15031 Mare	1.2 – 30	0.4 – 0.5	
15041 Mare	1.2 – 30	0.6 – 0.7	
15231 Mare	1.2 – 30	0.5 – 0.6	
Exolith LMS-1 Mare	0-900		0.735 ± 0.006
Off Planet OPRL2N Mare	0-900		0.720 ± 0.003
CSM-LMT-1 Mare	0-900		0.724 ± 0.007

*Apollo data from Carrier et al. (1991). *n.b.,* Liu et al. (2008) reported aspect radio modes of ~0.7 for Apollo soils 10084, 12001, 15041, 70051, and 79221.

+ Camsizer measurement.

Particle Size Distribution

The D(50) size values derived from the Camsizer optical analysis should be equivalent to the "median" size values (determined by sieving) compiled in Table 7.8 of the Lunar Regolith chapter of the Lunar Sourcebook (McKay et al., 1991). Table 2 presents the comparison. We note that the values of the Exolith simulants (74 and 78 μm) are at the upper end, but within range of the sieve medians reported for actual lunar soils.

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. The particle size distribution determined by weighing sieved grain size splits is fairly consistent with the results from the Camsizer instrument (Fig. 4). Both indicate a 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 μm). Our results show a shallower PSD curve (closer match to the Apollo average) than the PSD shown on the Exolith fact (aka spec) sheets for these two samples, which could indicate variations in the PSD between batches.

Table 2: Comparison of median particle sizes of lunar samples with the D(50) values for the lunar simulants studied here.

Sample	**Sieving median size (μm)***	**Camsizer D(50) (μm)**
Luna 20 – Highland	70 – 80	
Apollo 16 – Highland	101 – 268⁺	
Exolith LHS-1 Highland		74.3 ± 2.2
Off Planet OPRH3N Highland		36.3 ± 4.2
CSM-LHT-1 Highland		122.0 ± 2.1
Apollo 11 – Mare	48 – 105	
Apollo 12 – Mare	42 – 94	
Apollo 15 – Mare	51 – 108	
Apollo 17 – Mare	42 – 166⁺	
Exolith LMS-1 Mare		78.1 ± 1.6
Off Planet OPRL2N Mare		36.4 ± 1.8
CSM-LMT-1 Mare		140.6 ± 11.4

*From McKay et al. (1991), Table 7.8.

⁺ Mean value, no medians reported for Apollo 16 or 17.

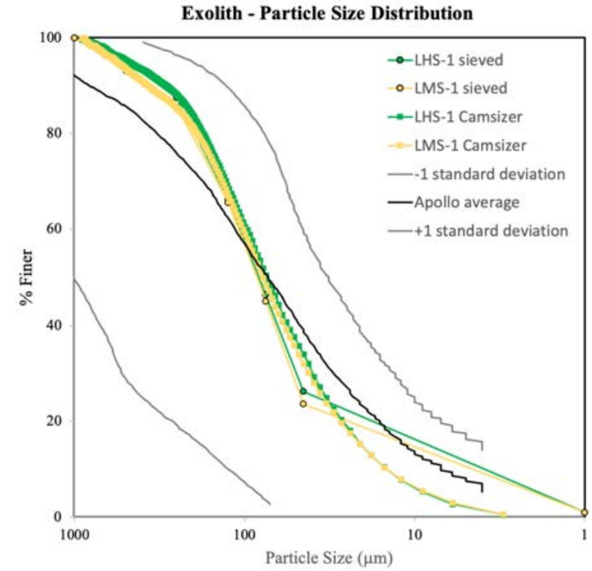
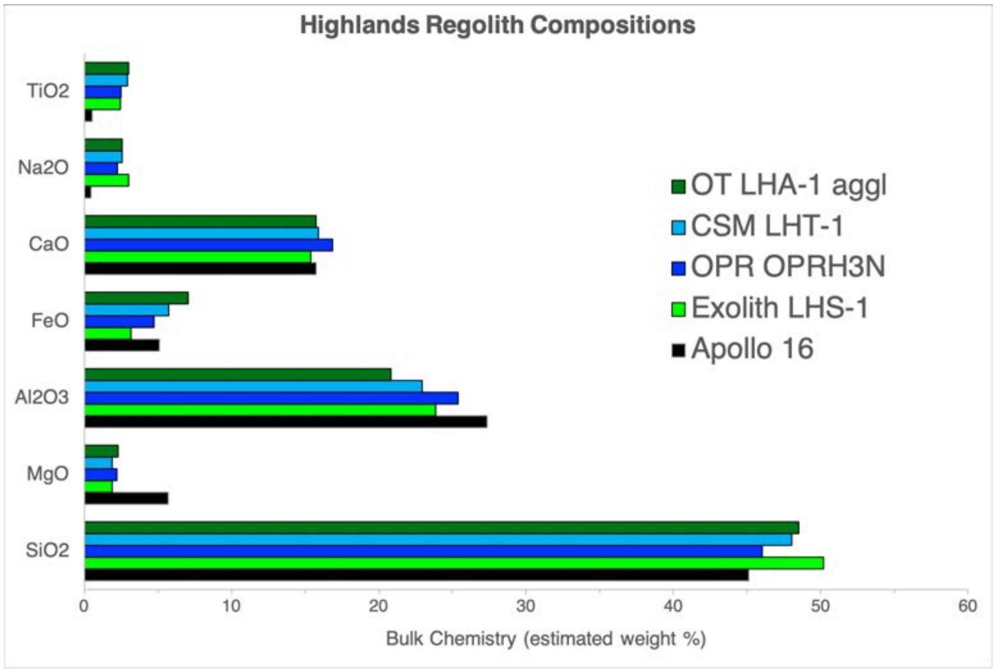


Figure 4: Cumulative particle size distribution of Exolith simulants in comparison to Apollo samples.

Composition and Mineralogy

The Exolith highland simulant LHS-1 provides a fairly good compositional and mineralogical match to the lunar highland regolith. The bulk chemical composition is largely similar (Fig. 5), though there is a fairly substantial difference in the sodium abundance. This is likely due to higher sodium abundance in GreenSpar plagioclase (An_{83}, Gruener *et al*. 2020) relative to lunar plagioclase). LHS-1 also has higher titanium and lower magnesium and iron than Apollo 16 highland regolith (Fig. 5). The bulk composition derived here is fairly similar to the composition reported by Exolith in the LHS-1 spec sheet. XRD analyses of the bulk LHS-1 sample reveal a mineralogy that includes 87% anorthite with the remaining phases equally divided between forsterite olivine (Mg_2SiO_4) and groutite ($MnO·OH$) (Fig. 7, Table 3). These results are consistent with optical examination of the sample (e.g., Figs. 2 and 6). The proportion of plagioclase, mafics (including pyroxene, olivine, lithics), and opaque minerals (i.e., groutite) of LHS-1 (Fig. 7a) provides an excellent match to a typical Apollo 16 highland regolith (Fig. 7b). However, groutite results from weathering Fe-bearing minerals. A process that is not present on the Moon. We note that all simulants produced from terrestrial rocks will contain hydrated mineral species that may provide fewer ideal matches to lunar regolith for some applications (e.g., water/oxygen extraction) and these difference need to be considered on a case-by-case basis. We also note that SEM maps show that nearly one-fourth of the mass of LHS-1 is mafic materials, of which a significant portion must be basaltic glass (Fig. 6). However, lunar highlands glass largely shares the anorthositic to anorthositic-noritic composition of the local material from which it is derived. Though this basaltic glass is not a good analog for agglutinitic glass, it is a reasonable compositional analog for mare basalts that contaminate the highlands as a result of impact mixing. SEM maps show that nearly one-fourth of the mass of LHS-1 is mafic materials, of which a significant portion must be basaltic glass (Fig. 6). However, lunar highlands glass largely shares the anorthositic to anorthositic-noritic composition of the local material from which it is derived. Though this basaltic glass is not a good analog for agglutinitic glass, it is a reasonable compositional analog for mare basalts that contaminate the highlands as a result of impact mixing.



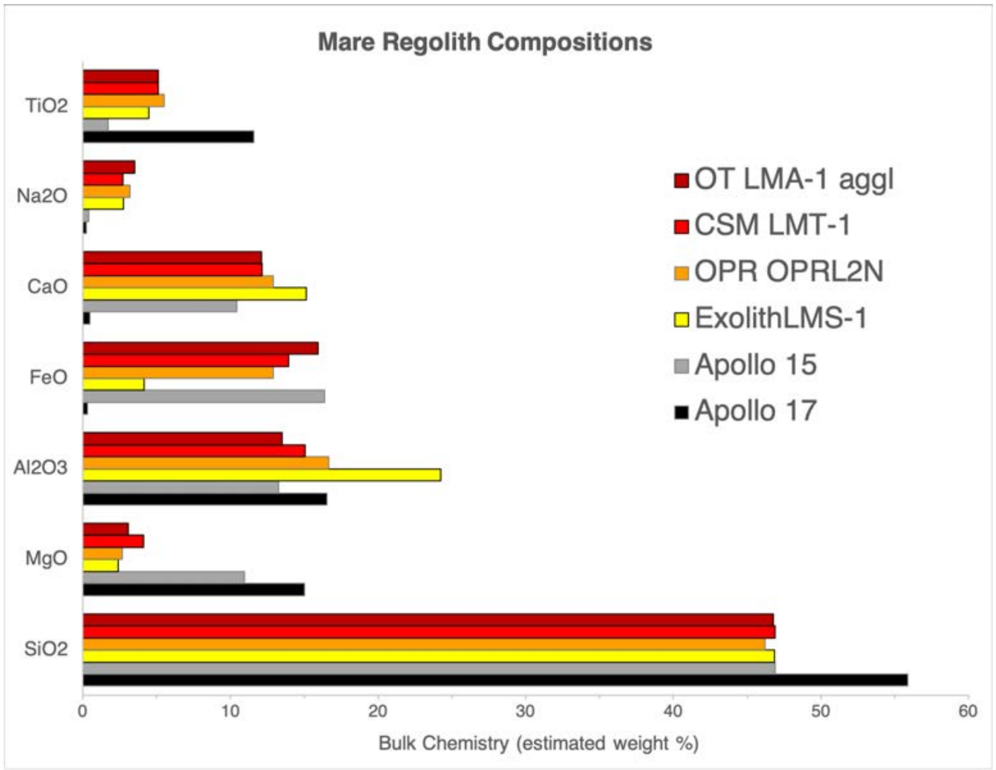


Figure 5: Compositional comparison between the highland simulants and average Apollo 16 regolith (top) and the mare simulants and average Apollo 15 and 17 mare regolith (bottom). Apollo soil compositions from Table 7.15 of McKay et al. (1991), normalized to include only the oxides shown here. For the simulants analyzed for this study, the oxidation state of Fe was not measured and all Fe was assigned to FeO. All oxides derived from XRF elemental data except Na_2O, which was an average from SEM compositional maps.

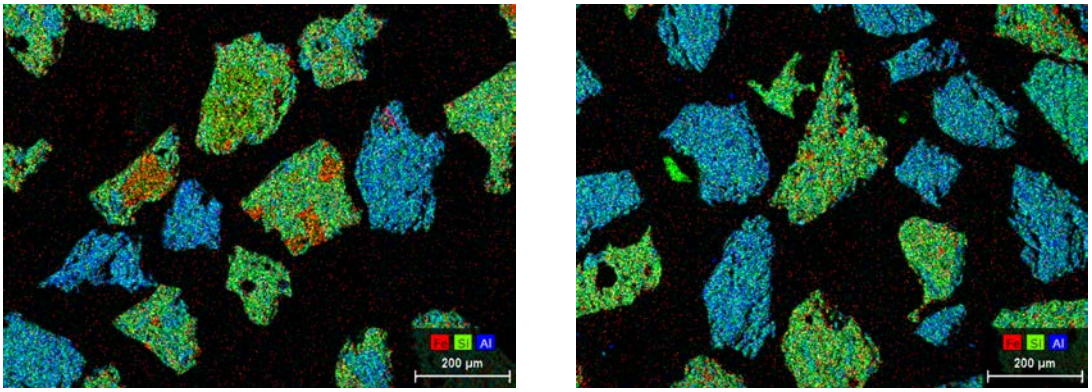


Figure 6: EDS elemental maps of Exolith LHS-1 (left) and LMS-1 (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green particles are mafic minerals and lithic fragments (basaltic materials, pyroxenes, olivines), and blue particles are plagioclase.

The composition and mineralogy of the Exolith lunar mare simulant LMS-1 also provides a general match to Apollo regolith samples. LMS-1 is substantially more sodic than lunar mare regolith (Apollo 15 and Apollo 17 soils provide a comparison for low- and high-titanium mare basalts) and has a higher abundance of magnesium and a lower abundance of iron (Fig. 5). We assumed all iron is present as Fe^{2+}O, but it is likely (and unavoidable) that there is a significant fraction of (Fe^{3+})$_2$O$_3$. The fact sheet from Exolith indicated that the TiO$_2$ content was 7.3 wt%, which was slightly higher than derived from our XRF data (Fig. 5). Therefore, LMS-1 has intermediate TiO$_2$ values (Fig. 5). XRD analyses of LMS-1 reveal a mineralogy that includes 100% anorthite (Table 3, Fig. 7). These results are not consistent with optical examination of the sample (e.g., Fig. 3). The XRD results suggest that the mafic components included in LMS-1 are very glassy, lacking the ordered mineral structure required for XRD identification. As a result, the apparent (crystallized) proportion of plagioclase, mafic minerals (including pyroxene and olivine), and opaque minerals of LMS-1 (Fig. 7c) provides a very poor match to a typical low-titanium Apollo 15 mare regolith (Fig. 7d). Exolith does note in their simulant report that the glass-rich basalt used in their simulants has many phases that may limit the diagnostic use of the XRD technique. SEM analyses of the 125-250 μm size split (Fig. 6) reveals mineral proportions more consistent with what is observed for lunar mare regolith (e.g., Figs. 7d, 7e).

Table 3: Semi-quantitative abundances of crystalline phases present in lunar regolith simulants (vol %).

Company	**Exolith**		**Off Planet Research**		**CO School of Mines**		**Outward Technology**	
Simulant	**LHS-1**	**LMS-1**	**OPRH3N**	**OPRL2N**	**LHT-1**	**LMT-1**	**LHA-1**	**LMA-1**
Type	Highland	Mare	Highland	Mare	Highland	Mare	HL aggl	M aggl
Plagioclase	87	100	100[1]	100	100	77[1]	100[1]	76[1]
Olivine	6.5	-	-	-	-	-	-	-
Pyroxene	-	-	-	-	-	23	-	24
Groutite	6.5	-	-	-	-	-	-	-

[1] Phase ID = Labradorite, (all other “plagioclase” were identified as anorthite).

Since the Exolith simulants are produced by mixing together individual minerals, lithic fragments, and glass components, their relative abundances can be adjusted based upon user needs. For example, the basaltic glass from LHS-1 could be removed or substituted, and larger quantities of ilmenite could be added to LMS-1 to create a high-titanium mare simulant.

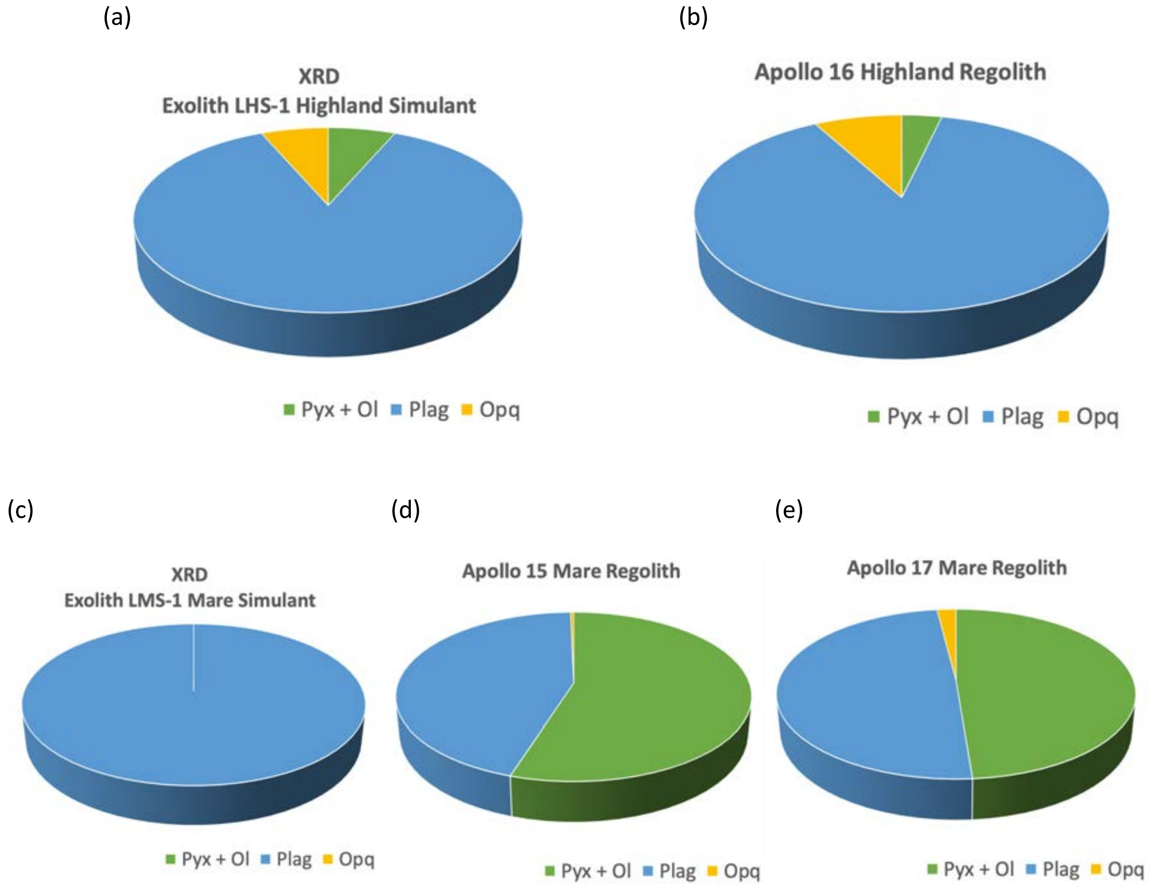


Figure 7: Mineralogical comparison between the Exolith regolith simulants and Apollo regolith, including (a) XRD of Exolith highland simulant LHS-1, (b) Apollo 16 highland regolith 67461, (c) XRD of Exolith mare simulant LMS-1, and (d) Apollo 15 low-titanium mare regolith and (e) Apollo 17 high-titanium mare regolith. XRD analyses sense only crystallized materials (bulk sample). Apollo regolith mineralogy derived from Table 7.2 of the Lunar Sourcebook as determined by Simon et al. (1981) using optical identification and excludes agglutinates, glass components, and lithic clasts.

Supply Chain and Quality Control

Between 2020 and 2021, Exolith has shipped ~20 tons of simulant requested by customers around the world with orders ranging from 1k to 20+ kg (average order is ~5 kg). Their most requested simulant is the lunar highland simulant LHS-1. In 2020, Exolith shipped 2 tons of simulant and, in the first 6 months of 2021, they had already shipped several tons. Representatives stated that more recently they are getting more requests for larger quantities (100s-1000s of kg) recently. Their production rate is currently ~500 kg/week, with a few batches of 50-60 kg being made daily. Exolith is capable of providing as much simulant as is required by the community and have solved several limiting factors this past year. First, they switched their feedstocks for both anorthosite and glassy basalt so that availability of feedstock does not limit their production. Also, in July 2021, Exolith moved their operations facility to a new, larger facility that will allow them to store more feedstock and increase batch sizes. A site visit to their new facility is planned when their operations are resituated and travel is less limited by the ongoing pandemic.

Exolith representatives emphasized that over the last year they have made an effort to provide greater transparency on their products, including providing compositional information and data on their website. This includes a Fact

Sheet for each simulant that states the mineralogy as mixed, bulk chemistry (XRF), particle size distribution, displays a Fourier Transform Infrared (FTIR) spectrum, and gives information regarding the particle size and bulk density. In addition, Exolith provides a document entitled Exolith Simulant Constituent Report that contains source, idealized mineralogy, XRD mineralogy, and XRF bulk composition (oxides) of the lithologies used to make simulants. On their website, Exolith states that the mineralogy, bulk chemistry, particle size distribution, volatile release, and derivative properties (e.g., spectral reflectance, magnetic susceptibility) of their simulants are “well-simulated”. However, they acknowledge that their simulants have limited applicability in terms of the particle shape, oxidation/weathering state, trace elements and isotopes, hazardous components (e.g., asbestosform serpentine in asteroid simulants), and reactivity (e.g., adsorbed H_2O from terrestrial environment).

Exolith does employ some quality control techniques during production process. The composition of the batch source material is verified with XRD when it arrives at their facility. In addition, they test mixed batches for particle size regularly. Beyond that, there main effort to ensure quality and consistency is by using well established processes (e.g., standard crushing protocol that defines the length of crushing time and sieving) and utilize a standard simulant recipe to measure components by weight for each batch. The composition of the final product is not verified for each batch. The oxide values reported in the spec sheets do match fairly well to those determined for this study, 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 is a small for-profit business that recently relocated from Lacey, Washington to Everett, Washington. The company was originally founded 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.

Available Simulants

Off Planet Research offers a variety of lunar simulants based on three feedstocks: Archean anorthosite from the Shawmere Anorthosite Complex in Ontario, Canada (An_{78}; Battler and Spray, 2009), 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), 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.) Agglutinates can be added upon request. Although OPRH3N was evaluated for the 2020 assessment, the sample provided was done as a “rapid response” portfolio simulant rather than their “scientific grade” that better reflects the typical particle size distribution of their simulants. Therefore, for this assessment we re-examined the OPRH3N simulant from their “scientific grade” portfolio (Fig. 8).

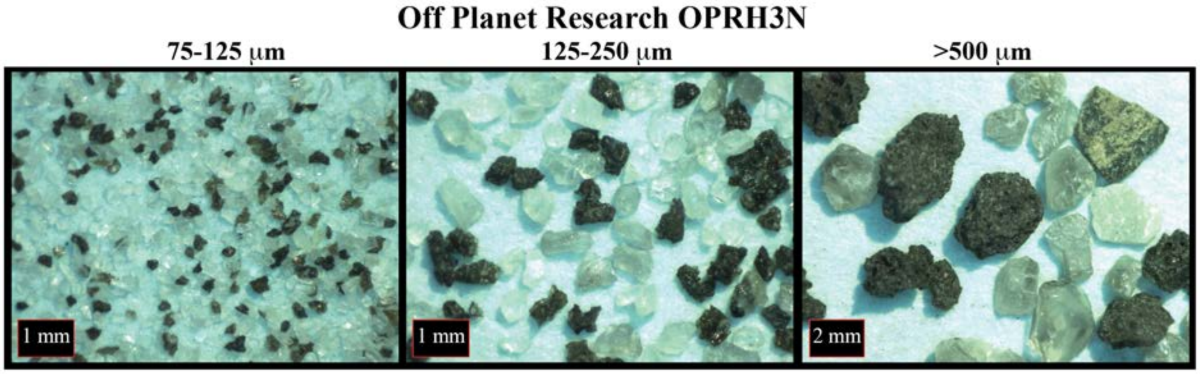


Figure 8: Off Planet Research highland simulant OPRH3N, shown at three different size fractions. The light particles are anorthosite and the dark particles are basaltic cinder.

The mare simulants include OPRL2N (90% basaltic cinder, 10% anorthosite) and OPRL2NT, which contains ilmenite (77% basaltic cinder, 8.6% anorthosite, 14.4% ilmenite) to mimic high-titanium mare materials. Agglutinates can be added upon request. Again, although OPRL2N was evaluated for the 2020 assessment, the sample provided was done as a “rapid response” portfolio simulant rather than their “scientific grade” that better reflects the typical particle size distribution of their simulants. Therefore, for this assessment we also re-examined the OPRL2N simulant from their “scientific grade” portfolio (Fig. 9).

Off Planet Research also produces agglutinates in bulk, which are created from the base simulants and thus share the same chemical compositions. These agglutinates 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 (they have stated in a conference publication that they “replicate the natural formation process by micro-meteorite strike” (Roux and Roth, 2017)). The agglutinate simulants were not re-evaluated for this assessment.

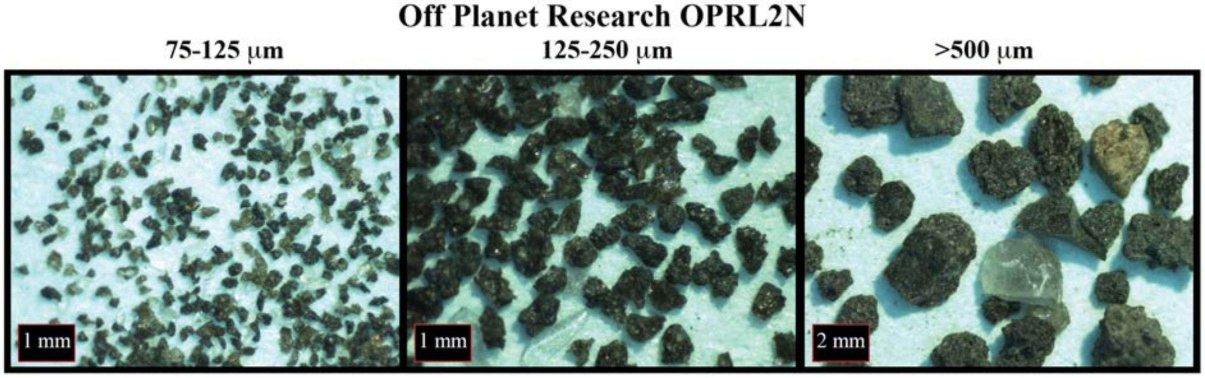


Figure 9: Off Planet Research mare simulant OPRL2N, a low-titanium mare basalt analog. The dark particles are basaltic cinder, light particles are anorthosite

Unique among the four providers discussed here, Off Planet Research also produces an icy regolith simulant (OPRFLCROSS2), with volatile compositions that match those of the LCROSS findings (Colaprete *et al*., 2010). The ices are deposited from a vapor onto super-cooled regolith simulant particles, in an effort to mimic the likely deposition process of ices on the Moon, and altering the geotechnical properties of the soil (Roux *et al*., 2019). Currently, the icy simulants must be produced and experimented on at the Off Planet Research facilities. Off Planet Research was recently awarded a National Science Foundation (NSF) Small Business Innovation Research (SBIR) grant to conduct research and development into providing cost-effective artificial mixtures of ice and soil found on the Moon to “accelerate the development of space resource extraction”. No nanophase iron is included in the Off Planet simulants.

Finally, Off Planet Research has recently started producing a simulant with increased magnetic response. Although this simulant is commercially available, it is not listed separately on their website because it is a customized product. This simulant is designed to suit the client’s research in terms of the base composition and magnetic response. A company representative noted that it tends to be geared towards lunar highland simulants because terrestrial anorthosites have almost no 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.

Particle Morphology

The aspect ratio values determined via Camsizer analysis for the two Off Planet simulants, OPRH3N and OPRL2N, are provided above in Table 1. The aspect ratio values of ~0.7 indicate that the particles have a low to moderate degree of elongation. The simulant particles may be slightly less elongated (have higher aspect ratios) but are closest to aspect ratios of lunar particles. Again we note that because the available data for the Apollo soils is for the lower end of the regolith size range and the simulant data are for the entire <1000 μm fraction, this conclusion is tentative.

Particle Size Distribution

Table 2 reports the D(50) particle-size values for the Off Planet highland and mare simulants that we tested. The Off Planet simulants D(50) values (~36 μm) fall just below the lower end of the range of actual lunar samples for which data are available. Figure 10 is a cumulative plot of particle-size distribution for the Off Planet simulants, as determined by our sieve analysis and by the Camsizer. For reference, the plot also shows curves that represent the range for lunar soils (data of Carrier (2003) as presented by Rickman et al. (2013)). We note that the two vials of both OPRH3N and OPR2LN were provided for our assessment; we used one vial to performing sieving and subsequent analyses and the other vial for Camsizer analyses.

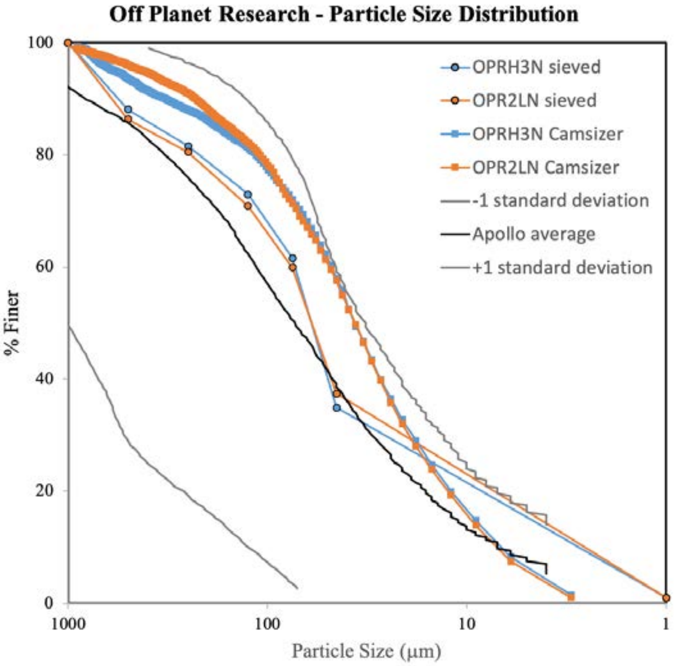


Figure 10: Cumulative particle size distribution of Off Planet Research simulants in comparison to Apollo samples.

The particle size distribution determined by weighing sieved grain size splits differs from the results from the Camsizer instrument, but both follow a similar trend (Fig. 10). Both indicate a PSD that is within 1 standard deviation of an average of Apollo samples, but the Off Planet Research samples do have a relatively greater abundance of larger particles (>75 μm).

Composition

Our initial compositional and mineralogical analysis of the highland simulant show an overall compositional match to Apollo 16 highland regolith (Fig. 5), although OPRH3N has a greater abundance of sodium, likely due to the fact that the Shawmere anorthosite is more albitic (An_{78}; Battler and Spray, 2009) than most lunar anorthosite. This highland simulant also has higher titanium and lower magnesium than typical lunar mare basalts (Fig. 5). XRD analyses of OPRH3N highland simulant reveal a mineralogy that includes 100% plagioclase (labradorite, An_{50-70}) (Fig.

12, Table 3). These results are not consistent with optical examination of the sample (Fig. 11). The XRD results suggest that the mafic components included in OPRH3N are very glassy, lacking the ordered mineral structure required for XRD identification. As a result, the apparent (crystallized) proportion of plagioclase, mafic minerals (including pyroxene and olivine), and opaque minerals of OPRH3N (Fig. 12a) provides a very poor match to a typical Apollo 16 highland regolith (Fig. 12b). However, SEM analyses of the 125-250 μm size split (Fig. 6) reveals much higher proportion of mafic materials in that size split.

Our initial compositional and mineralogical analysis of the mare simulant show an overall match to Apollo 15 low-titanium mare regolith (Fig. 5), although OPRL2N has a greater abundance of sodium. In addition, it contains higher titanium and lower magnesium (Fig. 5). XRD analyses of the OPRL2N mare simulant also show a mineralogy that includes 100% plagioclase (anorthite) (Fig. 12, Table 3). These results are not consistent with optical examination of the sample (Fig. 11). The XRD results is consistent with mafic components that are very glassy within OPRL2N, lacking the ordered mineral structure required for XRD. As a result, the apparent (crystallized) proportion of minerals of OPRL2N (Fig. 12c) provides a very poor match to a typical Apollo 15 low-titanium and Apollo 17 high-titanium mare regoliths (Fig. 12d). However, SEM analyses of the 125-250 μm size split (Fig. 11) reveals a much higher proportion of mafic materials within this size split.

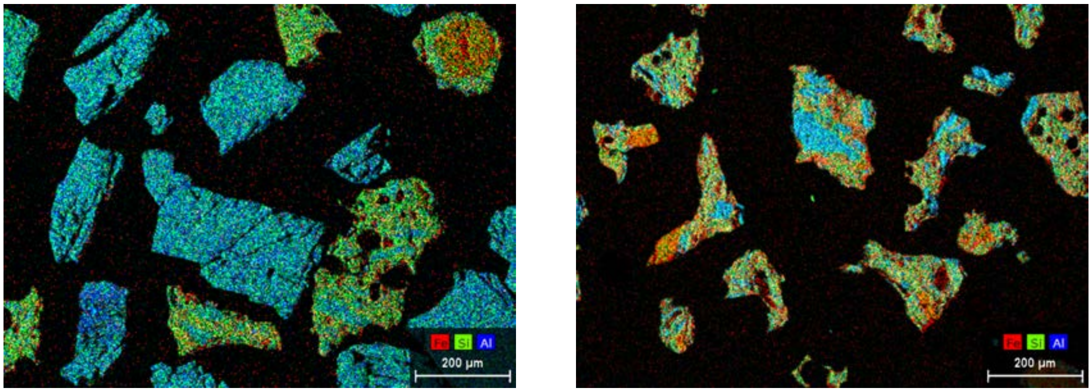


Figure 11: EDS elemental maps of OPRH3N (left) and OPRL2N (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green/orange particles are mafic minerals and lithic fragments (basaltic materials, pyroxenes, olivines), and blue particles are plagioclase.

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 user needs. Their production rate is ~25 kg/day for the highland and mare simulants and ~2kg/day for agglutinates. Given sufficient notice, one metric ton of the lunar mare and highland simulants could be delivered within eight weeks. Specialty simulants, especially those with additives, do have longer lead times. If agglutinates need to be added to the simulant, the delivery time would increase to approximately 10 weeks. A company representative noted that smaller orders can take longer due to assembly time more than production time and that the time required can also be dependent on the number of pre-existing orders. They are always trying to increase their production rate to scale with industry needs. Because current orders are in the range of tens of kilograms, larger scale orders should be discussed well in advance so Off Planet Research could determine if additional personnel and/or equipment are required to ensure delivery date. This is also true for specialty simulants (e.g., magnetic simulants) so they have sufficient time to discuss necessary additives and produce the simulant.

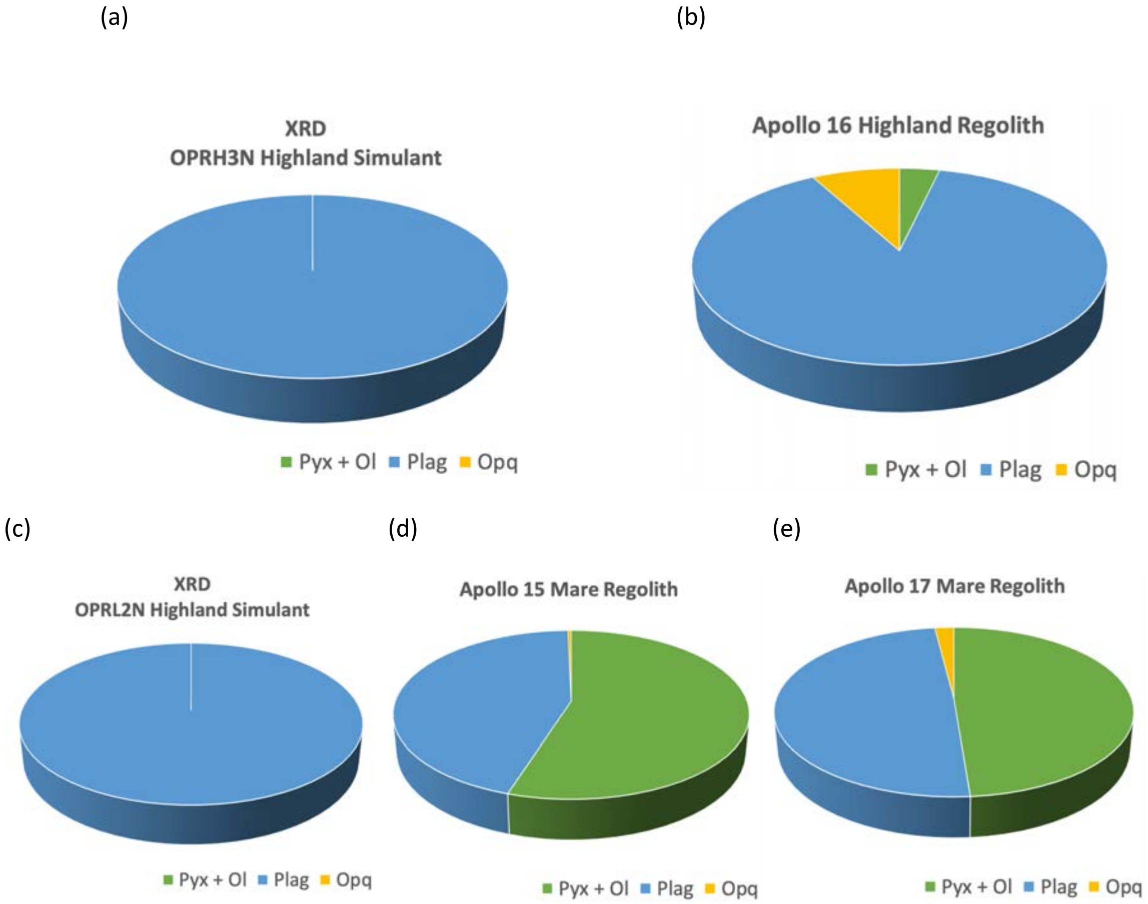


Figure 12: Mineralogical comparison between the Off Planet Research regolith simulants and Apollo regolith, including (a) XRD of OPRH3N, (b) Apollo 16 highland regolith 67461, (c) XRD of OPRL2N, and (d) Apollo 15 low-titanium mare regolith and (e) Apollo 17 high-titanium mare regolith. XRD analyses sense only crystallized materials. Apollo regolith mineralogy derived from Table 7.2 of the Lunar Sourcebook as determined by Simon et al. (1981) using optical identification and excludes agglutinates, glass components, and lithic clasts.

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 all simulants. 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) is just beginning, but the university has a long history of producing geotechnical simulants for terrestrial applications. The new 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. Professor Cannon previously worked at the Exolith Labs at the University of Central Florida where he gained experience developing and creating regolith simulants. The CSM team spent early 2021 prototyping the simulant production process and fine tuning their simulant compositions. Their first order was shipped in June 2021. Their goal is to provide high fidelity simulants with good quality control and consistency across batches.

Available Simulants

CSM currently produces several Mars simulants (CSM-MGS-1, CSM-MGS-1C, and CSM-MGS-1S) as well as 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 to the appropriate grain size by the supplier. CSM also uses an ash mined from a commercial basaltic cinder quarry near the southern flank of Merriam Crater, Arizona (the same source used for JSC-1). The basaltic material is crushed at CSM to the appropriate grain size.

The CSM lunar highland simulant CSM-LHT-1 (Fig. 13) 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 (McCay *et al*., 1994).

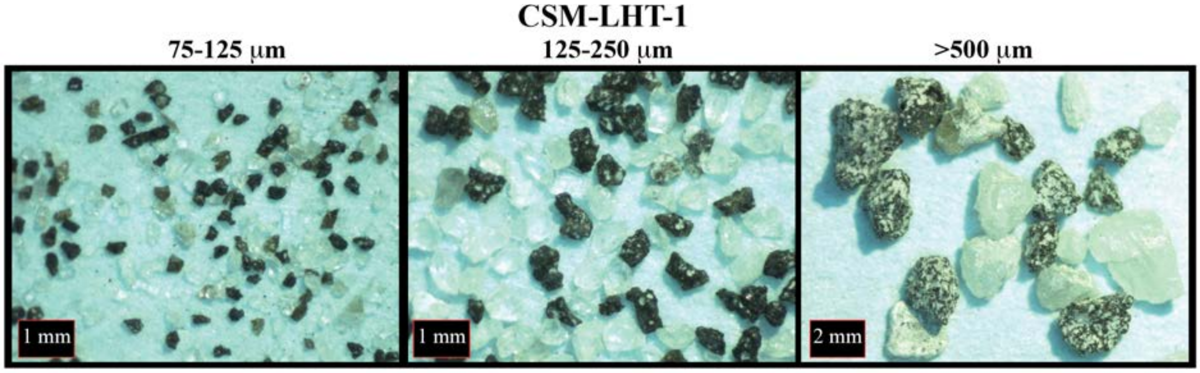


Figure 13: CSM Lunar Highland Simulant (CSM-LHT-1), shown at three different size fractions. The light particles are largely anorthosite and the dark particles are mainly basaltic glass.

The CSM mare simulant CSM-LMT-1 (Fig. 14) represents a low- to moderate-titanium mare and is entirely composed the Merriam Crater basaltic cinder. This basaltic cinder consists of a mixture of minerals and glassy materials. It has a fined-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 *et al.*, 2006). CSM does not include nanophase iron in any of their simulants or produce synthetic agglutinates.

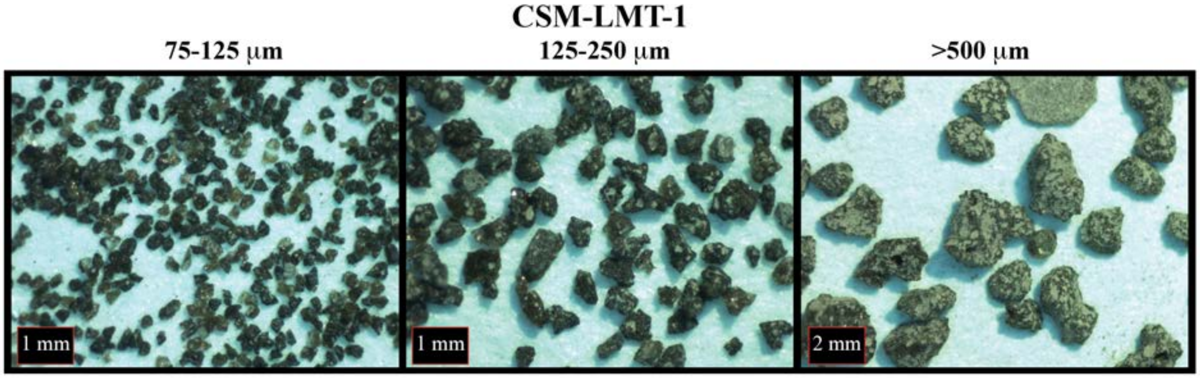


Figure 14: CSM Mare Highland Simulant (CSM-LMT-1), shown at three different size fractions. The light particles are largely anorthosite and the dark particles are mainly basaltic glass.

Particle Morphology

The aspect ratio values determined via Camsizer analysis for the two simulants, CSM-LHT-1 and CSM-LMT-1, are provided above in Table 1. The aspect ratio values of ~0.72 indicate that the particles have a low to moderate degree of elongation. However, the simulant particles may be somewhat less elongated (have higher aspect ratios) than the true lunar particles. Once again we note that the available data for the Apollo soils is for the lower end of the regolith size range and the simulant data are for the entire <1000 μm fraction, so this conclusion is tentative.

Particle Size Distribution

Table 2 reports the D(50) particle-size values for the CSM highland (122 μm) and mare (141 μm) simulants that we tested. The CSM simulants exceed or fall at the upper end of the range of actual lunar samples for which data are available (Table 2). Figure 16 is a cumulative plot of particle-size distribution for the CSM simulants, as determined by our sieve analysis and the Camsizer. For reference, the plot also shows curves that represent the range for lunar soils (data of Carrier (2003) as presented by Rickman et al. (2013)).

The particle size distribution determined by weighing sieved grain size splits differs from the results from the Camsizer instrument (Fig. 15). Both indicate a PSD that is within 1 standard deviation of an average of Apollo samples, but the CSM samples do have a relatively greater abundance of larger particles (>10 μm).

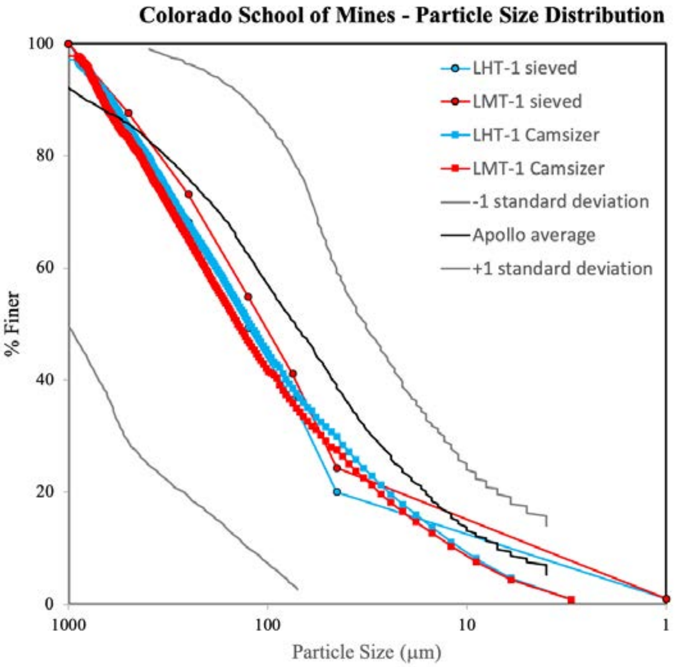


Figure 15: Cumulative particle size distribution of CSM simulants in comparison to Apollo samples.

Composition

Our initial compositional analysis of the highland simulants shows a fairly good match to Apollo highland regolith (Fig. 5 and 16), although CSM-LHT-1 has a greater abundance of sodium than a typical lunar regolith due to the sodic nature of the plagioclase feedstocks. It also appears to contain higher titanium and lower magnesium (Fig. 5). XRD analyses of CSM-LHT-1 highland simulant reveal a mineralogy that includes 100% plagioclase (anorthite, An_{90-100}) (Fig. 17a, Table 3). This is not consistent with optical examination of the sample (Fig. 13). The XRD results suggest that the mafic components included in CSM-LHT-1 are glassy, which results in the apparent (crystallized) mineralogy of CSM-LHT-1 (Fig. 17a) providing a very poor match to a typical Apollo 16 highland regolith (Fig. 17b). SEM analyses of the 125-250 μm size split (Fig. 16) reveal a much higher proportion of mafic materials.

Our compositional analysis of the mare simulant CSM-LMT-1 shows a fairly good match to Apollo mare regolith (Fig. 5 and 16), although CSM-LMT-1 contains more sodium than a typical lunar regolith. Many oxides match best to the Apollo 15 low-titanium mare regolith, although titanium is intermediate within the mare regolith (Fig. 5). XRD analyses of CSM-LMT-1 mare simulant show that it includes 77% plagioclase (labradorite, An_{50-70}) and 23% pyroxene (Fig. 17, Table 3), which appears to be low proportion based on SEM mapping (Fig. 16). The XRD results suggest that some of the mafic components included in CSM-LMT-1 lack the ordered mineral structure required for XRD identification so that the apparent (crystallized) proportion of minerals of CSM-LMT-1 (Fig. 17a) provides a poor match to a typical Apollo mare regolith (Fig. 17b). XRD analyses of the CSM-LMT-1 mare simulant also show a mineralogy that includes 77% plagioclase (labradorite, An_{50-70}) and 23% pyroxene (Fig. 12, Table 3). These results are not consistent with optical examination of the sample (Fig. 14), which shows the sample is dominated by mafic components. The XRD results suggest that most of mafic components lack the ordered mineral structure required for XRD identification. As a result, the apparent (crystallized) proportion of minerals of CSM-LMT-1 (Fig. 17c) provides a very poor match to a typical Apollo 15 low-titanium mare regolith (Fig. 17d). However, SEM analyses of the 125-250 μm size split (Fig. 11) reveals a much higher proportion of mafic materials within this size split.

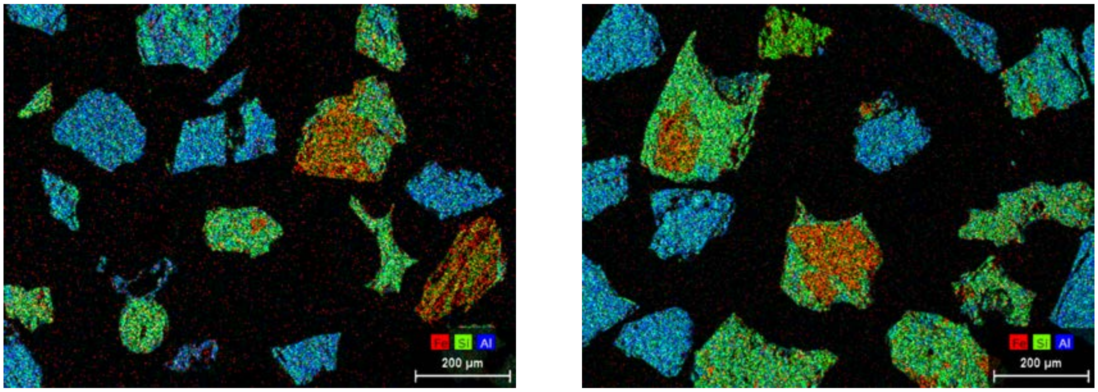


Figure 16: EDS elemental maps of CSM-LHT-1 (left) and CSM-LMT-1 (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green particles are mafic minerals and lithic fragments (basaltic materials, pyroxenes, olivines), and blue particles are plagioclase.

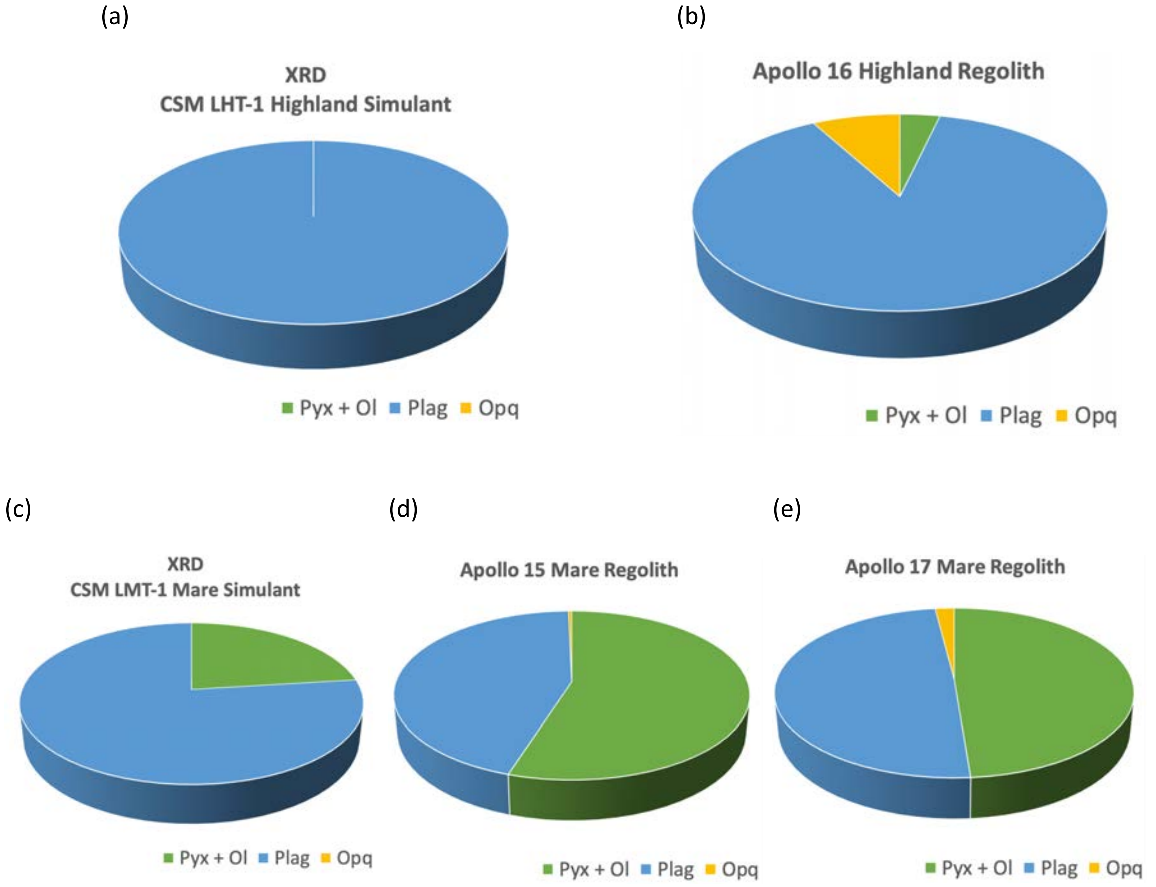


Figure 17: Mineralogical comparison between the Colorado School of Mines regolith simulants and Apollo regolith, including (a) XRD of CSM-LHT-1, (b) Apollo 16 highland regolith 67461, (c) XRD of LMT-1, (d) Apollo 15 low-titanium mare regolith and (e) Apollo 17 high-titanium mare regolith. XRD analyses sense only crystallized materials (bulk sample). Apollo regolith mineralogy derived from Table 7.2 of the Lunar Sourcebook as determined by Simon et al. (1981) using optical identification and excludes agglutinates, glass components, and lithic clasts.

Supply Chain and Quality Control

CSM currently has ~20 tons each of the GreenSpar Anorthosite and the Merriam Crater basaltic cinder and do not anticipate supply chain issues in the future. They can currently 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. CSM also strives to make the simulants affordable and offers their lunar simulants for as low as $3 per kg if sufficient quantities are ordered (higher prices for smaller quantities) .

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. Since the simulant lab is still getting set up, the specific metrics and figures of merit are to be identified for quality control. However, once they are finalized, every batch will be checked. Future 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: OUTWARD TECHNOLOGIES

Company Background

Outward Technologies (formerly Blueshift) is a small for-profit business in the Denver, Colorado area. The company currently has eight personnel employed by the company (three full-time employees and two part-time employees). The company was founded by Dr. Ryan Garvey (the principal research scientist) and Andrew Brewer (the principal research engineer) to focus on soil mechanics with an eye toward in-situ , solar powered 3D printing for lunar building materials. The geotechnical properties of lunar soil can be affected by the agglutinate contents, so the company has established a parallel operation to produce reliable agglutinate simulants to include in lunar regolith simulants. Outward Technologies is currently funded by SBIRs from NASA and NSF, including Phase 2 funding to increase their production and research capabilities. Current techniques produce agglutinate simulants in what they call “batch mode”, but could be scaled up to a continuous production if the market supports that.

Available Simulants

Outward Technologies does not manufacture a complete lunar soil simulant. Rather, they produce simulated agglutinates through a method that they have developed (and for which a patent is pending) to partially melt a feedstock, and then bond the unmelted and melted portions. This process is designed to result in particles that, like lunar agglutinates, are irregularly shaped and composed of glass and mineral/lithic fragments. Their process of creating agglutinates has been improved recently and a representative stated that they can now guarantee that 100% of grains are either agglutinates or contained within agglutinates.

Outward Technologies is agnostic to the feedstock and can use any feedstock for mare or highlands based on user needs. Simulated agglutinates can then be mixed with the feedstock from which they were created (*e.g.*, Exolith LHS-1 or JSC-1) in proportions that would match the expected site-specific lunar soil conditions (up to 60% agglutinates). No nanophase iron is included in the Outward agglutinate simulants. Recently, Outward Technologies has tacked several unique requests including very small agglutinates and agglutinates with magnetic properties.

For the current assessment, Outward Technologies supplied two new agglutinate simulants, one lunar highland agglutinate LHA-1 (Fig. 18) and one lunar mare agglutinate LMA-1 (Fig. 19). The feedstocks for these agglutinates are proprietary information and were not identified at this time.

Particle Morphology

The Outward agglutinate simulants consist of a mix of particles that are visually similar to agglutinates (glassy, irregularly shaped) and lithic and mineral clasts from the starting feedstock. In particular, the highland agglutinate sample (Fig. 18a) is largely comprised of lithic and mineral clasts, and it appears that only a small fraction of the particles are the glass-bound assemblages expected of agglutinates. The mare agglutinates sample (Fig. 18b) appears to have a larger fraction of agglutinate-like particles, however further analysis is required to determine their glass/mineral clast ratio and vesicularity.

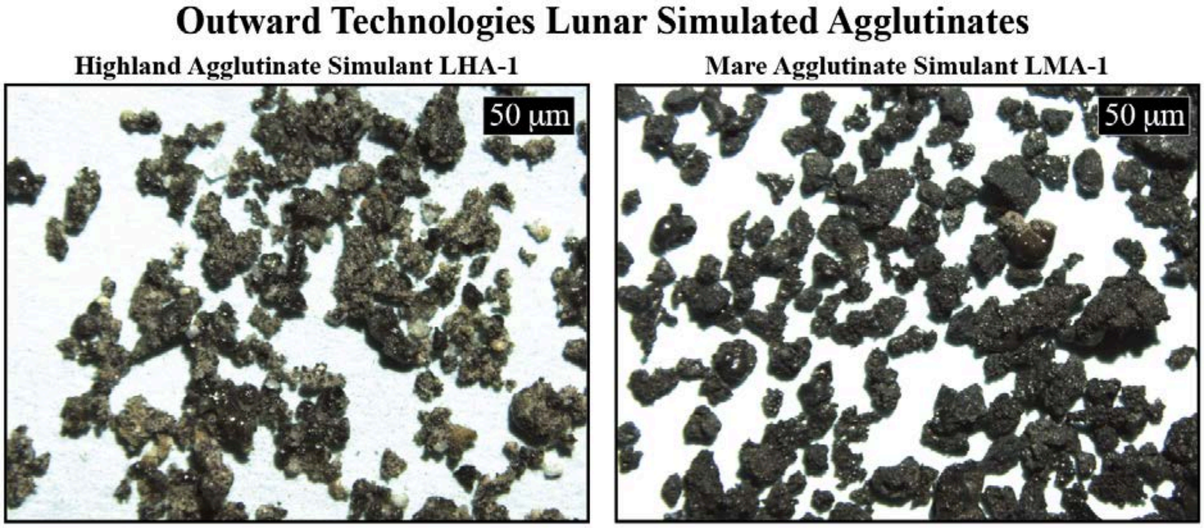


Figure 18: Bulk Outward Technologies Lunar Highland Agglutinate Simulant LHA-1 (left) and bulk Outward Technologies Lunar Mare Agglutinate Simulant LMA-1 (right).

Particle Size Distribution

Data for the particle size distribution of the agglutinate simulants was not collected since there is no available data for the size distribution of true lunar agglutinates with which to make a comparison. We focus here on the morphology and composition of the Outward agglutinate simulants.

Composition

The composition and mineralogy of the Outward Technologies agglutinates is dependent on the starting feedstock, which can be varied according to user needs. The feedstocks used to make LHA-1 and LMA-1 were not revealed by Outward Technologies. Overall, the composition of both the highland agglutinate and mare agglutinate simulants show a similarity to Apollo compositions (Fig. 5).

The highland agglutinate simulant LHA-1 contains more sodium than lunar highland regolith, suggesting a sodic plagioclase is used. It also includes more iron and titanium and less magnesium than a highland regolith. XRD analyses of LHA-1 highland agglutinate simulant reveal a mineralogy that includes 100% plagioclase (labradorite, An$_{50\text{-}70}$) (Fig. 20a, Table 3). The XRD results suggest that the mafic components included in LHA-1 lack the ordered mineral structure required for XRD identification, which is consistent with the glassy nature of agglutinates. The EDS map of LHA-1 (Fig. 19) reveals the presence of some mafic mineral/lithics (orange and green patches within Fig. 19) contained within dominantly felsic materials (Fig. 19), with empty vesicles indicating melting and entrapment of gas bubbles as the sample quenched.

The mare agglutinate simulant LMA-1 contains more sodium than lunar highland regolith, suggesting a sodic plagioclase is used. It includes less MgO than a mare regolith, but an intermediate amount of TiO_2 relative to the low- and high-titanium mare regolith (Fig. 3). XRD analyses of LMA-1 mare agglutinate simulant reveal a mineralogy that includes 76% plagioclase (labradorite, An$_{50\text{-}70}$) and 24% pyroxene (Fig. 20b, Table 3). The XRD results suggest that both mafic and felsic materials were only partially melted, although the remaining crystalline material is dominated by plagioclase. The EDS map (Fig. 19) of OT-LMA-1 reveals the presence of some felsic material (blue patches) that appear to be contained within mafic materials (green to orange areas). The sample also contains empty circular vesicles indicative of gas bubbles trapped within melted material that quenched rapidly.

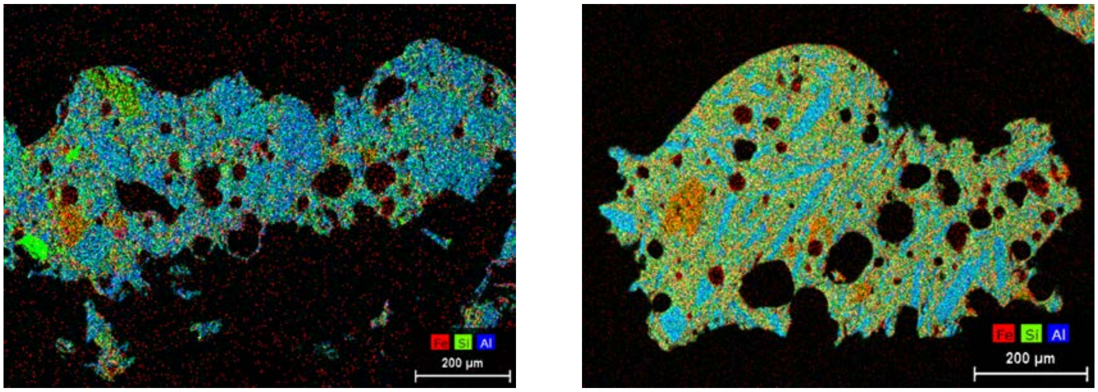


Figure 19: EDS elemental maps of Outward Technology LHA-1 (left) and LMA-1 (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green and orange/red areas are mafic rich material and blue areas are felsic, plagioclase-rich material.

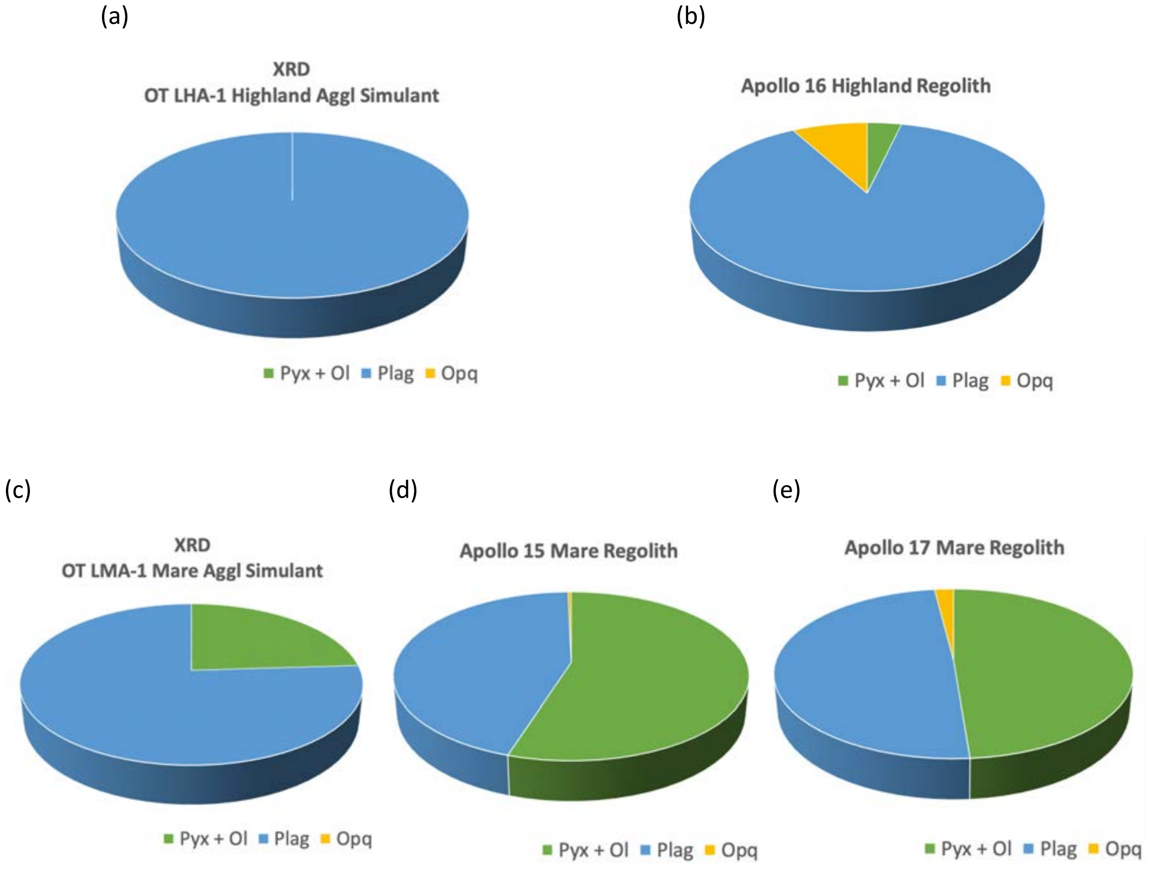


Figure 20: Mineralogy of Outward Technologies regolith agglutinate simulants, including (a) XRD of LHA-1, (b) Apollo 16 highland regolith 67461, (c) XRD of LMA-1, (d) Apollo 15 low-titanium mare regolith and (e) Apollo 17 high-titanium mare regolith. XRD analyses sense only crystallized materials (bulk sample), so this technique would be insensitive to the glassy materials expected within agglutinitic simulants. The detection of minerals within the samples suggest that not all material was melted by the process used to create the agglutinate simulants.

Supply Chain and Quality Control

Improved techniques has led to more complete agglutinization of samples (100% agglutinates per batch), meaning increased production rate overall. Currently, Outward Technologies produces “research quantities” at a rate of 1.5-2 kg per hour, but note that time varies depending on the composition of the feedstock. In addition, they note that they can now tailor the particle size groups to research requirements.

Thus far, Outward Technologies has produced 5-10 kg of simulated agglutinates, mostly of the LMA-1 (mare agglutinate) variety. Currently, the agglutinates are created using a batch process that produces up to 0.5 kg in 2–4 hours per batch (time varies depending on the composition of feedstock (mare or highland)). With improvements to lab capabilities to allow continuous production, Garvey estimates they could create 100 kg of agglutinates in 1 month (current rate is ~3 kg/day). Recent improvements have made the batch process 100% efficient (i.e., all grains are either glass or contained within glass).

Outward Technologies focuses on mineralogy, morphology, and strength of agglutinates in simulant design and fabrication. Currently, each batch is sized by mechanical sieving to achieve the desired particle size distribution (PSD), which varies between batches. Particle shape is evaluated qualitatively by optical microscope. In addition, a third party lab collects detailed PSD and particle shape data on select batches. Additional characterization data (e.g., cohesion, shear strength, angle of repose) are collected as part of independent research at Outward Technologies and at other institutions. The company is open to feedback from stakeholders and customers, and they are happy to modify processes to meet customer needs.

OTHER SIMULANTS

This past year, two simulant providers (Exolith, CSM) have begun using Anorthosite from Hudson Resources Inc., could also be considered further. Hudson Resources has mined substantial quantities of anorthosite, known as White Mountain Anorthosite or GreenSpar, from Kangerlussuaq, Greenland. This anorthosite has a plagioclase content of 82–94 wt%, an An# of 83, and currently tens to hundreds of tons of crushed GreenSpar are stored in warehouses in South Carolina (Gruener *et al*., 2020). While this is not a complete simulant, as it lacks glass and basaltic contaminants and includes other contaminants (*e.g.*, quartz, muscovite, and calcite), this bulk GreenSpar material could be an inexpensive option for some applications. We also note that their standard milled grain size (250 μm and below) lacks larger grain sizes displayed by Apollo regolith samples.

In addition, a terrestrial anorthite from the Miyake-jima volcano in Japan has been suggested as a good compositional and spectral analogue to plagioclase found in lunar ferroan anorthosites (Brydges *et al*., 2015). An average mineral chemistry of Miyake-jima anorthite megacrysts taken from ~10 locations across 5 anorthite particles revealed a chemistry that was An_{98}, making this an excellent Ca-rich terrestrial plagioclase for lunar work. There are currently no known commercial operations to quarry this material.

If simulants are to be used for their geotechnical properties alone, then inexpensive options include Glenn Research Center simulants, GRC-1 and GRC-3, created from silt and sand. We have not analyzed these simulants, but fairly comprehensive peer-reviewed literature that exists about their geotechnical properties (Oravec et al., 2010; He et al., 2013).

In addition, a new geotechnical lunar regolith simulant named Lunar Caves Analog Test Sites, or LCATS-1, has been developed between the WEX Foundation, the University of Texas at San Antonio, and the Southwest Research Institute (Hooper et al., 2020) and is available for purchase through Astroport Space Technologies. This simulant was developed to support education, scientific research, and engineering studies and is currently being used for studies in ISRU, construction, dust measurements, and test beds.

COMPARISON AND EVALUATIONS

Lunar Highland Simulants (Non-agglutinate Fraction)

Denevi *et al.* (2020) studied manually-removed agglutinate separates from sieved (125-250 μm) Apollo regolith samples, which left behind low-agglutinate regolith samples (Fig. 21a). We used this sample for comparison to our three highland regolith simulants (Fig. 21). The most obvious difference is that Apollo 16 regolith remnant displays much lower reflectance than the highland simulants. Apollo 62231 is mature regolith sample and the majority of the grains have been altered by space weathering. This means that the grain surfaces have rims containing nanophase iron, which lowers their overall reflectance (Lucey *et al*., 2006). Furthermore, whereas the simulants are mainly binary mixtures of anorthosite and basalt, the Apollo 16 sample contains fragments of breccias and noritic lithic fragments and the mafic components are more intimately mixed. We note that these difference will probably not have a substantial impact on the effectiveness of the simulants for most applications.

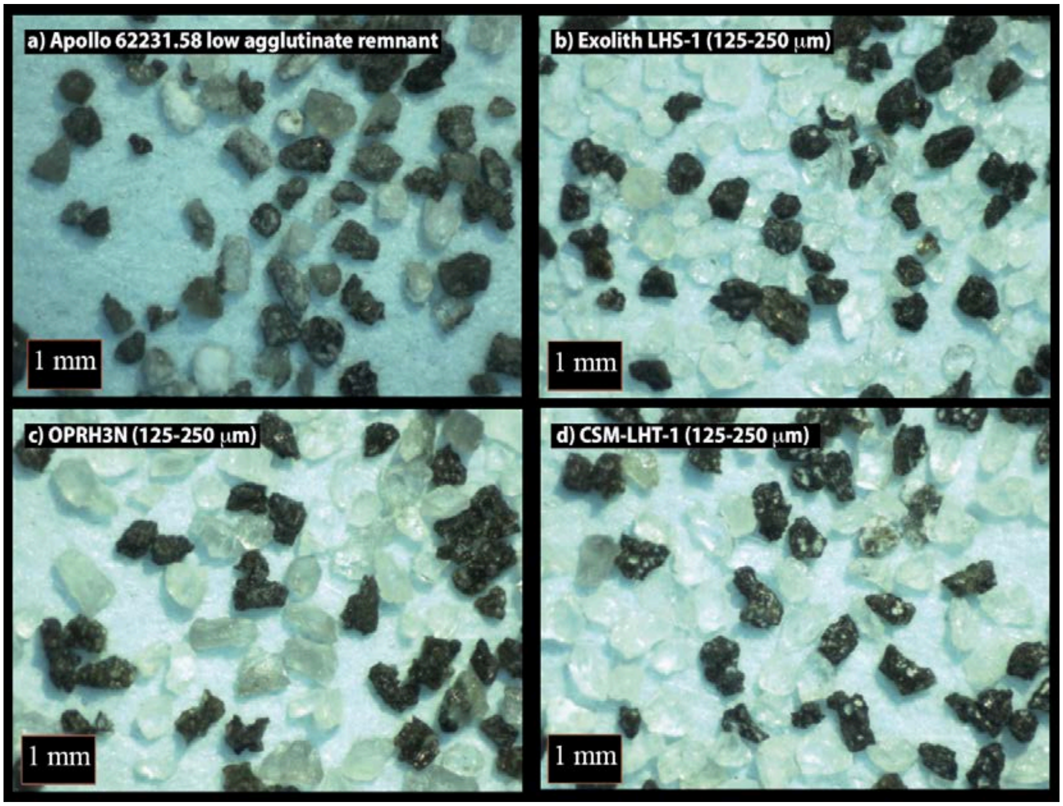


Figure 21: A comparison of a) the low-agglutinate remnant of Apollo 16 sample 62231.58 and lunar highland regolith simulants: b) the Exolith LHS-1; c) the Off Planet Research OPRH3N; and c) the CSM-LHT-1. Each has been sieved to 125–250 μm.

There is some variation the amount of basaltic cinder/glassy basalt that is mixed in with the anorthosite by the three vendors (Exolith: 25%, OPR:20%, CSM:30%). In addition, two vendors (Exolith and CSM) use the GreenSpar (An_{83}) anorthosite, while Off Planet Research uses the Shawmere Anorthosite (An_{78}). All three have a particle size distribution within one standard deviation of the mean for lunar soils, but with a steeper slope for cumulative particle size curve than is seen for an average Apollo regolith sample. These differences are minor, resulting is fairly similar compositions and variation from Apollo regolith compositions (Fig. 5). In applications where certain factors might be important, such as having low sodium plagioclase or the presence of nanophase iron, all three highland simulants are lacking and there is no simple solution to fix these issues. Terrestrial plagioclase generally is more sodic than lunar plagioclase and finding an abundant source of more calcic plagioclase (e.g., Miyaki-jima) is challenging. In addition, nanophase iron is difficult to produce and requires very reducing experimental conditions. Thus, we find that all the highland simulants are likely acceptable for most applications and when needed can be customized to address application requirements.

Lunar Mare Simulants (Non-agglutinate Fraction)

The mare simulants are compared to the low-titanium Apollo 15 regolith sample 15041 (Fig. 22a), which has also a soil from the Denevi *et al.* (2020) study where agglutinates were manually removed from a 125-250 μm size split. The three mare simulants show striking differences (Fig. 22), which are likely due to the formulas used to make the simulants. Exolith combines rocks (basalt, anorthosite) and minerals (pyroxene, olivine, ilmenite) to match lunar compositions, whereas Off Planet Research and CSM use only rock fragments (OPR: basalt and anorthosite; CSM: basalt). The Exolith LMS-1 appears to include more light colored minerals (aka felsic) than is present in the Apollo mare regolith sample (compare Figs. 23a and 23b). However, the mare simulants from both Off Planet Research and CSM appear to contain more mafic components, although we note that both have some felsic materials attached or embedded within the darker mafic components (Figs. 23c and 23d). These differences are not likely to be significant for most applications.

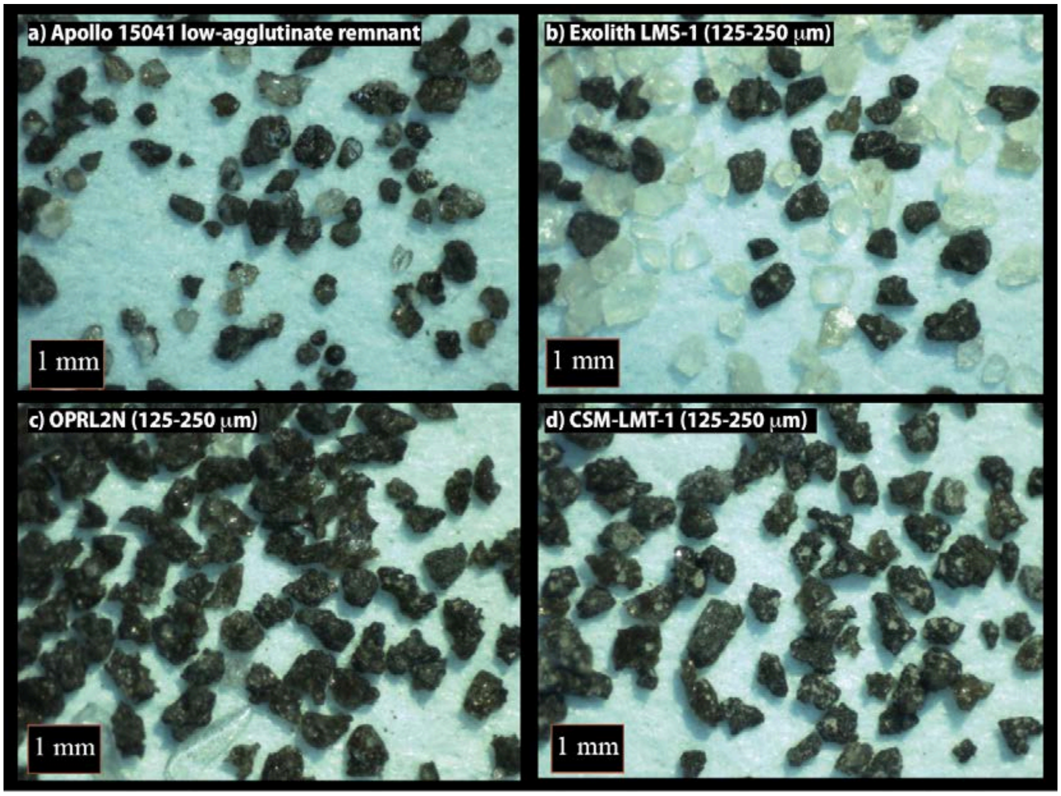


Figure 22: A comparison of a) the low-agglutinate remnant of Apollo 15 sample 15041and lunar mare regolith simulants: b) the Exolith LMS-1; c) the Off Planet Research OPRL2N; and c) the CSM-LMT-1. Each has been sieved to 125–250 μm.

In terms of their bulk compositions, the biggest difference between the Apollo mare regolith and simulants is in the sodium. Specifically, all mare simulants contain much higher Na_2O (~3 wt. %) when compared to Apollo mare regolith (<0.5 wt. % Na_2O, Fig. 5). This compositional difference affects the melting temperature of materials and could have important implications for some applications such as sintering of regolith to produce construction materials. In addition, all simulants exhibit an intermediate titanium value when compared to both Apollo low- and high-titanium mare regolith (Fig. 5), while many other oxides match more closely to the Apollo 15 low-titanium mare regolith. We also note that the Exolith mare simulant LMS-1 contains much higher aluminum and lower iron than the other mare simulants and mare regolith (Fig. 5), perhaps reflecting feedstock components used to make their simulant. These differences in FeO abundance could be of potential concern for specific applications, such as oxygen extraction (Cilliers et al., 2020l Lomax et al., 2020).

Agglutinate Simulants

We only evaluated agglutinate simulants from Outward Technology this year for two reason. First, Outward Technology changed the feedstock from which their highland agglutinate and mare agglutinate were created. Secondly, they stated that there have been significant improvements to the agglutinization batch process that resulted in 100% efficient (i.e., all grains are either glass or contained within glass). Therefore, we chose to re-evaluate their product for this year.

The Outward Technology highland agglutinate simulant LHA-1 does show a much greater level of agglutinization when compared to last year and much more visual similarity to Apollo 16 agglutinate separates from the study of Denevi et al. (2020) (Fig. 23). We did not sieve the LHA-1 sample for this study in order to maintain sufficient sample amount for various analyses. As a result, Figure 23 is comparing the Apollo 67461 agglutinate separate from the 125-250 μm size split to the bulk sample of LHA-1. This results in an obvious difference in the overall size of the agglutinate particles in the comparison. Ignoring this difference, there is a visual similarity to the Apollo 67461, with a glass-rich texture and evident welding of mineral and lithic fragments and overall low albedo we would expect from agglutinates.

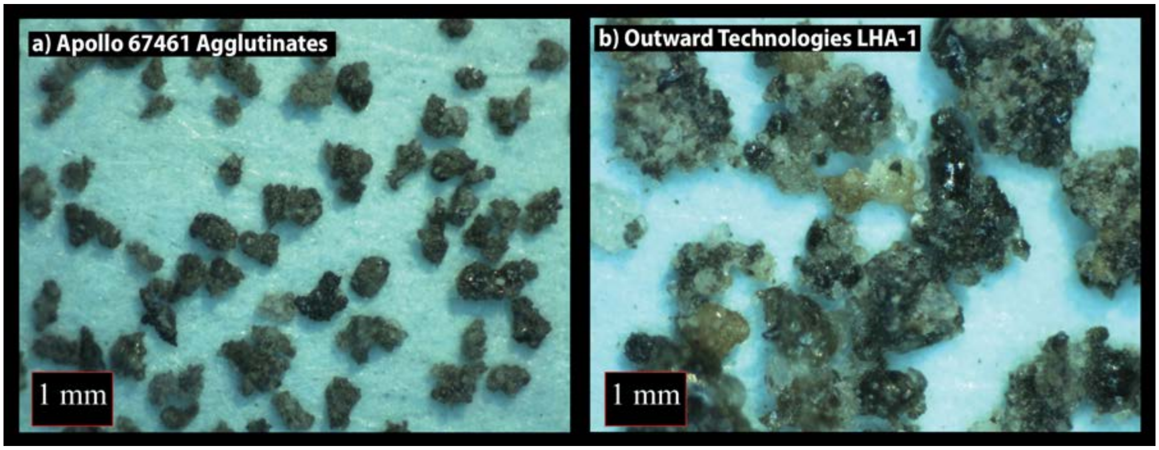


Figure 23: A comparison of a) the Apollo 67461 Agglutinate 125-250 μm separate from Denevi et al. (2020) and b) the bulk Outward Technologies LHA-1 Highland Agglutinate Simulant.

The Outward Technology mare agglutinate simulant LMA-1 also shows a much greater level of agglutinization when compared to last year and visual similarity to Apollo 15 agglutinate separates from the study of Denevi et al. (2020) (Fig. 24). We did not sieve the LMA-1 sample for this study in order to maintain sufficient sample amount for various analyses. As a result, Figure 24 displays the Apollo 15041 agglutinate separate from the 125-250 μm size split to the bulk sample of LMA-1. This results in an obvious difference in the overall size of the agglutinate particles in the comparison. Disregarding this difference, there is a visual similarity to the Apollo 15041, with a glass-rich texture and evident welding of mineral and lithic fragments. Unlike the highland agglutinate LHA-1, we do not observe obvious mineral fragments welded together, perhaps suggesting that the feedstock was a single rock lithology with no mineral additives.

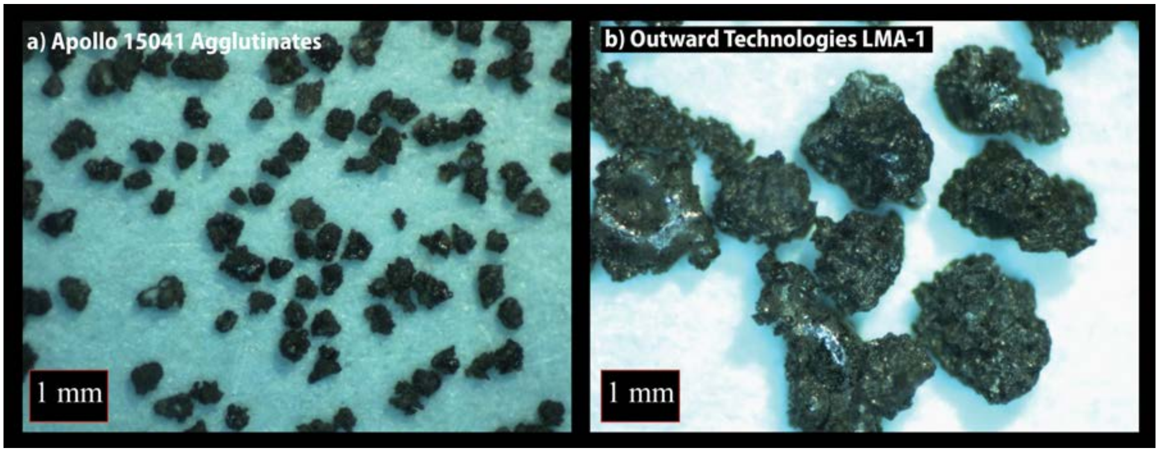


Figure 24: A comparison of a) the Apollo 15041 Agglutinate 125-250 μm separate from Denevi et al. (2020) and b) the bulk Outward Technologies LMA-1 Mare Agglutinate Simulant.

Suitability for Testing Oxygen Extraction Technologies

There are a variety of engineering and science objectives for the Moon that drive the need for regolith simulants with bulk and specific characteristics that approximate lunar materials (Simulant Working Group, 2010). Here we focus on evaluating the viability of the simulants provided by Exolith, Off Planet Research, Colorado School of Mines, and Outward Technologies for use in oxygen production (Table 4). Oxygen can be extracted from lunar regolith using several techniques and is a potentially abundant resource that would be vital for life support and spacecraft propulsion (Allen *et al*., 1996). The energy input required (and yield expected) for a given extraction technique depends on a number of material characteristics (Schrader *et al*., 2010). In Table 4, we evaluate simulants based on common and unique material characteristics identified for oxygen extraction methods described in Appendix 6 of the Simulant Working Group (2010).

Table 4: Comparison of selected regolith characteristics for each simulant in terms of their suitability for testing of oxygen extraction technology.

Important Regolith Characteristics (Oxygen Extraction)		Value[1]	Highland Simulants				Mare Simulants			
			Exolith LHS-1	Off Planet Research OPRH3N	CSM LHT-1	Outward Tech. LHA-1	Exolith LMS-1	Off Planet Research OPRL2N	CSM LMT-1	Outward Tech. LMA-1
			Green: simulant provides a close match to lunar soil in most aspects, **Yellow**: lacking in some aspect(s) but likely still acceptable; **Red**: poor match or no attempt to match.							
Bulk properties	Chemistry	Medium	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Mineralogy	High	🟨	🟨	🟨	N/A	🟨	🟨	🟨	N/A
Grain characteristics	Shape	High	🟨	🟨	🟨		🟨	🟨	🟨	
	Size Distr.	High	🟩	🟩	🟩		🟩	🟩	🟩	
Agglutinate characteristics	Glassiness	High	N/A	N/A	N/A	🟩	N/A	N/A	N/A	🟩
	Shape	High				🟩				🟩
Implanted Solar Particles[2]		Low	🟥	🟥	🟥	N/A	🟥	🟥	🟥	N/A
Reactivity		Medium	🟥	🟥	🟥		🟥	🟥	🟥	
Nanophase Fe		Low	🟥	🟥	🟥		🟥	🟥	🟥	
Magnetic Properties[3]		Low	🟥	🟥	🟥		🟥	🟥	🟥	

[1] Determined based on the variety of extraction methods that indicate the importance of a given characteristic (Simulant Working Group, 2010).

[2] An important attribute of lunar soils that cannot be replicated on Earth.

[3] Both Off Planet Research and Outward Technology have begun to work on simulants with magnetic response as customized products upon request, but we did not evalulate those simulants.

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.

It should also be pointed out that regolith simulants and even lunar regolith do not necessarily behave in the same way on Earth as they would on the Moon. The volatile constituents that are implanted in the surface of the grains by the solar wind are not present 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 (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. Where simulants are lacking (e.g., Table 4), 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 Exolith and Off Planet, 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 employs some quality control and have attempted to create a website with greater transparency regarding their simulants. Our results suggest that they have the particle size distribution and the compositions stated within the spec sheets match fairly closely to our current year measurements, but some variation may exist from batch to batch. 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. Outward Technology has also improved their process for creating agglutinates and can provide agglutinates from any feedstock simulant. 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.

FURTHER CHARACTERIZATION

This information has been gathered from conversations with each simulant provider, from data that they provided, and various provider publications. Exolith, Off Planet Research, Colorado School of Mines, and Outward Technologies all provided the LSII Lunar Simulants team at JHU-APL with samples of their products that were analyzed with various techniques (XRF, XRD, SEM, sieving, etc.) in a fashion similar to those used by previous studies for lunar samples. We have added several analyses this year to more fully characterize the simulants, but further chemical assessments should be added. For example, we would recommend XRD with Rietveld refinement to fully quantify the phases present and a more complete microprobe analysis of larger quantities of sample to better understand the mineral chemistry present in the simulants. These types of analyses could be especially important for specific applications, such as oxygen extraction. In addition, metrics for the assessment of the fidelity of chemical composition have been developed (*e.g.*, Chang and Ann, 2019) and a user-friendly simulant certification system is being developed (Deitrick and Cannon, 2021). We recommend collaborating with simulant experts such as John Gruener at Johnson Space Center to perform additional analyses. Supplementary work may seek to understand hydration, trace element composition, and oxidized contaminants, as well as to provide documentation of the importance of various simulant properties for specific use cases.

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