This assessment of lunar simulants was performed at the Johns Hopkins Applied Physics Laboratory. Its purpose is to share information about existing lunar simulants that may be used in technology development efforts for lunar surface operations. The report is preliminary and will be updated as further work is completed.

Lunar Simulant Assessment

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1. Introduction

Spurred by the Constellation Program, a 2010 report from LEAG and CAPTEM (Simulant Working Group, 2010) presented findings on the lunar regolith simulants that were available at that time (e.g., JSC-1, JSC-1A, NU-LHT) and their strengths and weaknesses for various uses. Excellent summaries of the history of, and the shortcomings of these simulants were presented by Taylor and colleagues (Taylor and Liu, 2010; Taylor et al., 2016). In the intervening decade, new simulants have become available that specifically address the limitations of the previous iterations. Here we present information on several simulants from this new generation, including new analyses of their particle size–frequency distribution, particle morphology, and composition, and their potential suitability for specific uses.

2. Methodology

Lunar simulant samples were obtained from three companies (CLASS Exolith Lab, Off Planet Research, and Outward Technologies, formerly Blueshift). Each sample was dry sieved into six particle size fractions (<45 µm, 45–75 µm, 75–125 µm, 125–250 µm, 250–500 µm, and >500 µm) in a similar fashion to analyses of some Apollo samples. The 125–250 µm size fraction was washed with ethanol to remove clinging fine particles.

An assessment of each simulant's particle morphology and visual similarity relative to types of lunar regolith was made for three size fractions (75–725 µm, 125–250 µm, >500 µm) using a binocular microscope. The particle size–frequency distribution for each soil was initially assessed by determining the mass of each size sieved fraction. We also characterized the size and shape of the particles in the samples using an instrument built by Retsch Technology, the Camsizer X2. The instrument operates by entraining a sample of granular material in a stream of air, which separates particles that are clinging together. The particles pass in front of a microscope that is connected to a high-speed camera. Built-in image-processing algorithms analyze the images and extract size and shape parameters. A velocity profile of the particles was created and a correction was applied to the measurement based on this profile, in order to ensure that the same particles are not measured twice. For each sample, three different aliquots (of ~100 mg each) were measured and the results were averaged. The particle size ($xc_{\min}$) is assigned to be the smallest of all maximum chords of the particle projection. A bin size of 3 µm was used 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). These represent the volume percent of particles below the specified diameter. For example, a value of D(50) = 75 µm indicates that 50% of the particles are less than 75 µm in diameter. Under the assumption that the grain density of particles is constant among the size bins, then volume percents as measured optically by the Camsizer should be equivalent to weight percents derived from sieve analysis.

The Camsizer system reports a number of shape parameters including, for each size bin:

- Aspect ratio (short axis/long axis, so that a spherical particle has aspect = 1, and more elongated particles have progressively smaller values).
- Sphericity: spht = 4piA/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.

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 SEM images. Image processing was used to determine the aspect ratio of a best-fit ellipse was determined (Fig. 1) and a parameter that they call "complexity", 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).

Another particle shape study is that by Liu et al. (2008), who examined five Apollo lunar soils and also 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. Liu et al. (2008) found that the frequency distribution of aspect ratios for all the lunar samples they 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.

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. Future work to examine the relationship between these parameters may prove beneficial for assessing simulants.

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).

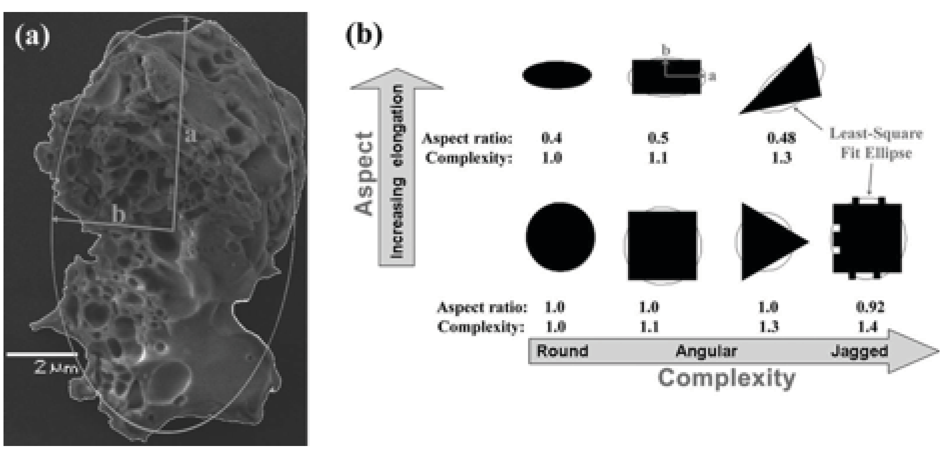

Fig. 1. Illustration of the parameters "aspect" and "complexity" employed by Liu et al. (2008, their Fig. 2).

Grain mounts were created using ~1–2 mg of particles from the 125–250 µm fraction of each sample. The particles were placed in silicone mold, mounted in epoxy, and polished using diamond pastes of progressively finer grits down to 0.25 µm. Each grain mount was then carbon coated, and analyzed in a Hitachi TM 3000 scanning electron microscope (SEM). Elemental compositions were determined via Energy-dispersive X-ray spectroscopy (EDS) using a Bruker Quantax 70. EDS elemental maps were collected for a portion of each grain mount. The compositional analysis performed quantitative, i.e., the EDS element maps provide relative abundances of each element such that mineralogy can be identified, and average elemental composition of the scene can be calculated. However, a more rigorous analysis of elemental abundances (such as via microprobe analysis) has not been performed.

A general assessment of supply chain and quality control came from discussions with representatives from each simulant producer and visits to each facility.

3. CLASS Exolith Lab

3.1 Company Background

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. Begun 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. Initial work focused on the production of asteroid simulants, but has expanded to include a variety of lunar and Martian simulants. As part of the current CLASS SSERVI node, Exolith is funded for the next five years. Exolith is managed by Dr. Kevin Cannon, a planetary scientist with deep knowledge of the relevant lunar geology. Exolith also offers complimentary consulting on simulant-related science to assist in the choice of and use of simulants. At the end of 2019, Exolith updated its equipment for improved production rate and consistency in production and increased its workforce.

3.2 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.

LHS-1 (Fig. 2) is primarily composed of anorthite (74 wt.%) that was mined from the Stillwater Igneous Complex (Stillwater Mining Company site) in Montana. The site is one of a handful of terrestrial geologic sites that has historically been used for their petrologic similarities with lunar materials (e.g., Raedeke and McCallum, 1980). The Stillwater anorthite provides a reasonable compositional match to the composition of the lunar highlands, though it is more albitic (An_{73-80} versus lunar An_{94-99}; Raedeke and McCallum, 1980; Papike et al. 1998, respectively). The glass that makes up 24 wt.% of the LHS-1 simulant is a basaltic cinder from the San Francisco volcanic field in Arizona and is not a close compositional match to the lunar highlands, but 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.% of basalt, ilmenite, pyroxene, and olivine.

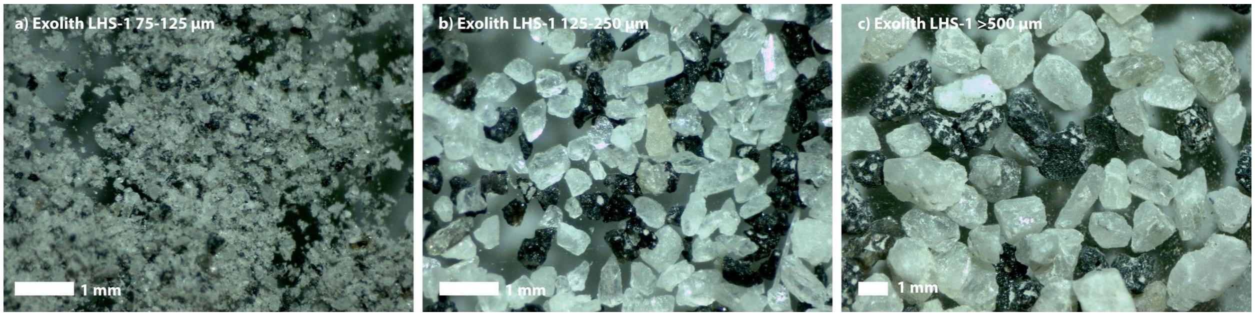

Fig. 2. Exolith Lunar Highland Simulant (LHS-1), shown at three different size fractions. The light particles are largely anorthosite and the dark particles are mainly basaltic glass.

The Exolith mare simulant, LMS-1 (Fig. 3), is intended to be representative of low- to moderate-titanium (in this case, 4.6 wt% TiO_2) mare, and is comprised of 38% pyroxene, 25% basaltic glass, 20% plagioclase, 11% olivine, 8% basalt, and 4% ilmenite in proportions based on “average” lunar basalt.

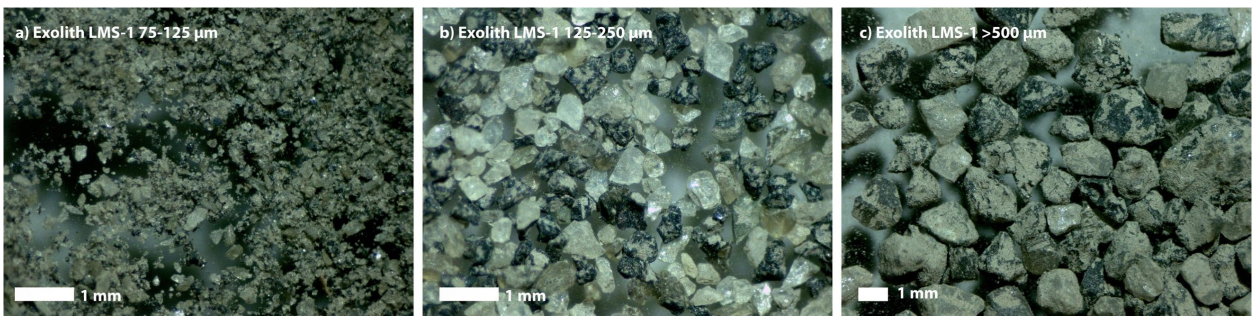

Fig. 3. Exolith Lunar Mare Simulant (LMS-1), shown at three different size fractions. LMS-1 consists of a mix of mineral and lithic fragments.

Exolith also produces a dust simulant (DUST-Y) with a mean particle size of ~8 µm. 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.

No nanophase iron is included in any of their simulants. Exolith does not produce synthetic agglutinates.

3.3 Particle Morphology

Table 1 provides a comparison of the aspect ratio data for lunar soils with 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 (~0.7) and correspond to a moderate degree of elongation. The aspect ratio value for the simulants corresponds well to 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.

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

Sample	Size Fractio n (µm)	Aspect Ratio Mode*	Aspect Ratio Median+
12001 mare	3.2–6.1	0.3–0.4	
14163 nonmare	1.2–30	0.6–0.7	
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 LHS-1 highland	0–900		0.72
Exolith LMS-1 mare	0–900		0.72
Off Planet OPRH3N highland	0–900		0.71
Off Planet OPRL2N mare	0–900		0.74
Off Planet OPRH3N agglutinates	0–900		0.68
Off Planet OPRL2N agglutinates	0–900		0.67
Outward LHA-1 agglutinates	0–900		0.71
Outward LMA-1 agglutinates	0–900		0.72

*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.

Although glass is included in the Exolith lunar simulants, the glass is a good analog for neither agglutinates nor lunar pyroclastic glasses in terms of particle shape. Agglutinates are highly irregular, and themselves 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 is thus similar in shape to the other grains in the simulant.

3.4 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 are at the upper end of the sieve medians reported for actual lunar soils.

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

Material	Sieving median size, µm+	Camsizer D(50), µm
Luna 20 - highland	70–80	
Apollo 16 - highland	101–268*	
Exolith LHS-1 highland		224
Off Planet OPRH3N highland		47.6
Apollo 11 - mare	48–105	
Apollo 12 - mare	42–94	
Apollo 15 - mare	51–108	
Apollo 17 - mare	42–166*	
Exolith LMS-1 mare		102
Off Planet OPRLN2 mare		42

+From McKay et al. (1991), Table 7.8.
*Mean value, no medians reported for Apollo 16 or 17.

Measurements of the mass of each sieved fraction of Exolith simulant provide a basis of comparison of the particle size frequency distribution of the simulants with Apollo soil samples. We find a strong deviation of the Exolith samples from lunar soils (Fig. 4), which is due to a relatively larger abundance of particles >500 μm in size. These results contrast with those available on the Exolith database, suggesting that relatively large variations in particle size distribution can occur from batch to batch.

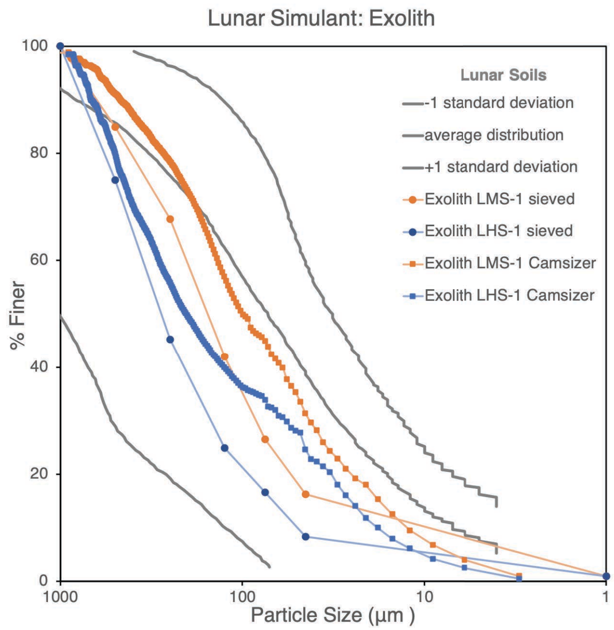

Fig. 4. Cumulative particle size distribution of Exolith simulants in comparison to Apollo samples.

3.5 Composition

The Exolith highland simulant LHS-1 provides a general, though not ideal, compositional match to the lunar highlands. The bulk chemical composition is largely similar (Fig. 5), though there is a fairly substantial difference in the sodium abundance (likely due to higher sodium abundance in Stillwater compared to lunar plagioclase). However, nearly one-fourth of the mass of LHS-1 is basaltic glass (Fig. 6), whereas glass in the lunar highlands largely shares the anorthositic to anorthositic-norite 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 the mare basalts that contaminate the highlands as a result of impact mixing.

The composition of the Exolith lunar mare simulant LMS-1 (Fig. 6) also provides a general match to Apollo regolith samples (Fig. 4). The largest differences are found in Na, Mg and Fe; LMS-1 is substantially more sodic than lunar mare regolith (Apollo 15 and Apollo 17 soils provide a comparison for low- and high-Ti mare basalts), has a higher abundance of magnesium, and a lower abundance of iron (Fig. 5). Note we assumed all iron is present as FeO, but it is likely (and unavoidable) that there is a significant fraction of Fe_2O_3. Though the fact sheet from Exolith indicated that the TiO_2 content was 4.6 wt%, we had a difficult time identifying any ilmenite in the EDS data and the average initial compositional estimate was just 1.5 wt% TiO_2.

Because 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.

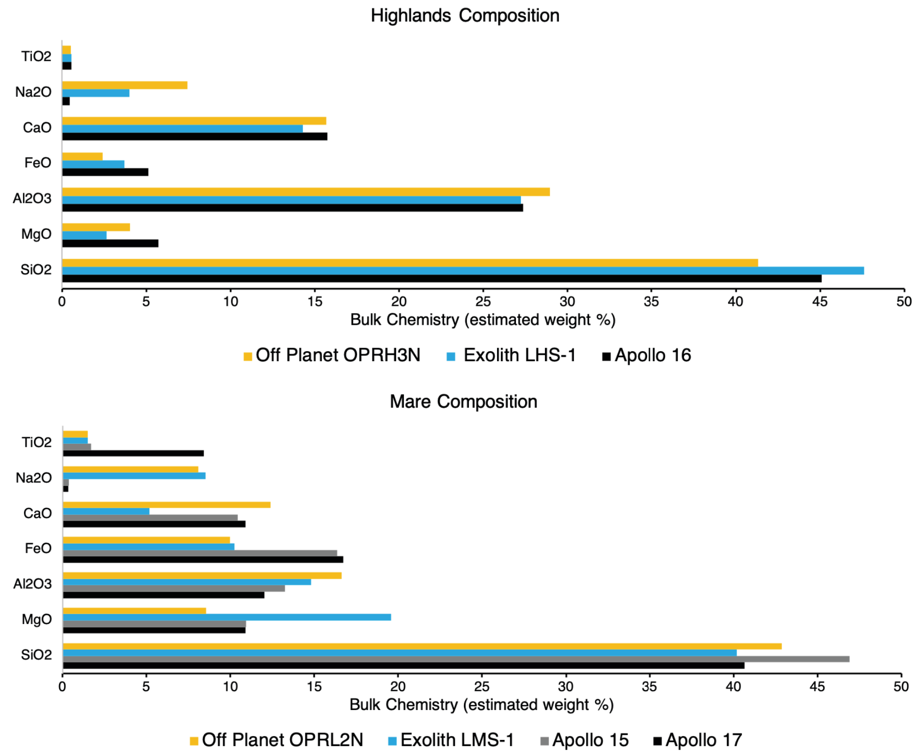

Figure 5. Initial compositional comparison between the Exolith and Off Planet highland simulants and average Apollo 16 regolith (top) and the mare simulants and Apollo 15 and Apollo 17 average mare regolith (bottom). Apollo soil compositions from Table 7.15 of McKay et al. (1991), all have been normalized 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.

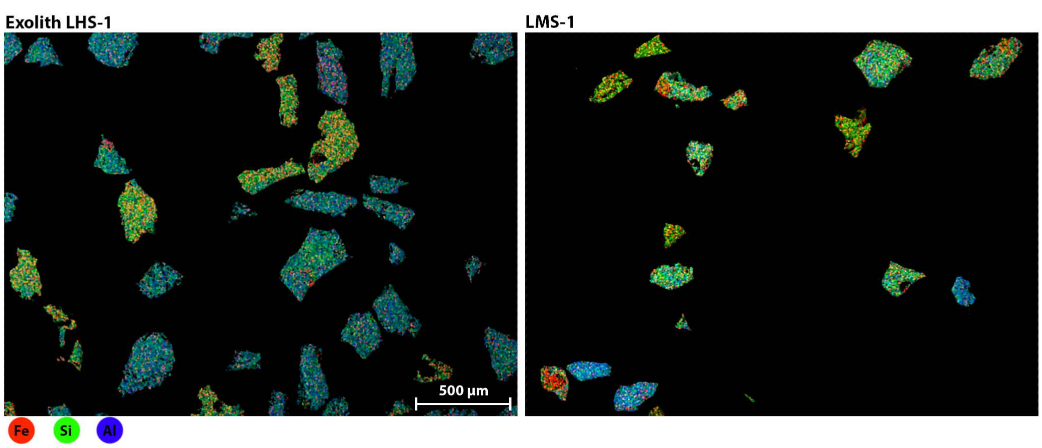

Figure 6. EDS elemental maps of Exolith LHS-1 (left) and LMS-1 (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green particles are mafic minerals and lithic fragments (basaltic materials, pyroxenes, olivines), and blue particles are plagioclase.

3.6 Supply Chain and Quality Control

Since forming in 2018, Exolith has shipped approximately 360 orders of simulants for a total mass of 2418 kg to 352 unique customers around the world. The largest requests have been for the MGS-1 Mars simulant and the LMS-1 lunar mare simulant. The average order is about 6 kg (requests of ≤1 kg will be processed free of charge, depending on shipping expenses), and average shipping time is approximately 10 days. Exolith is capable of providing as much as the community needs, pending availability of feedstock. Constraints on the feedstock availability include seasonal mining conditions. For example, Exolith is currently (January 2020) running low on Stillwater anorthosite and more cannot be obtained until weather improves in the spring. In response, the lab is now also obtaining White Mountain anorthosite mined in Greenland and stored in South Carolina, a component which we have not evaluated here.

Exolith emphasizes community response and relies on its wealth of lunar knowledge to deliver simulants that meet the community's needs. However, Exolith does not employ consistent or rigorous quality control techniques. The composition of the source material is not verified before processing into simulant. This could result in differences in composition from lot to lot, because, for example, terrestrial deposits like the Stillwater are not homogenous, but often layered. The grinding techniques are effective but vary from operator to operator, likely resulting in inconsistency in the grain size distributions between lots. The composition of the final product, including contamination level such as presence of alteration material, is not verified. It appears that the samples that we received indicate that lack of consistency and quality control may be an issue, given the differences in particle size distribution and titanium content differed from the fact sheets provided by Exolith. This absence of an additional process for quality control is likely a fundamental reason the response is rapid and the cost of the simulant remains low, i.e., a trade-off exists between process and verification versus responsiveness and affordability. Exolith has the potential, though not yet the capability, to provide additional quality control if requested.

4. Off Planet Research

4.1 Company Background

Off Planet Research is a small for-profit business located in Lacey, Washington. Currently, they have three full-time employees and a fourth consultant. 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 simulants, based on customer needs, and are working to expand their customer base and capabilities.

4.2 Available Simulants

Off Planet Research offers a variety of lunar simulants based on three feedstocks: anorthosite from the Shawmere 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 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 no farside lunar highland regolith samples have been collected, and a 20% basaltic component may be too high, though the percentage can be adjusted during creation.) Of these, we examined only OPRH3N (Fig. 7).

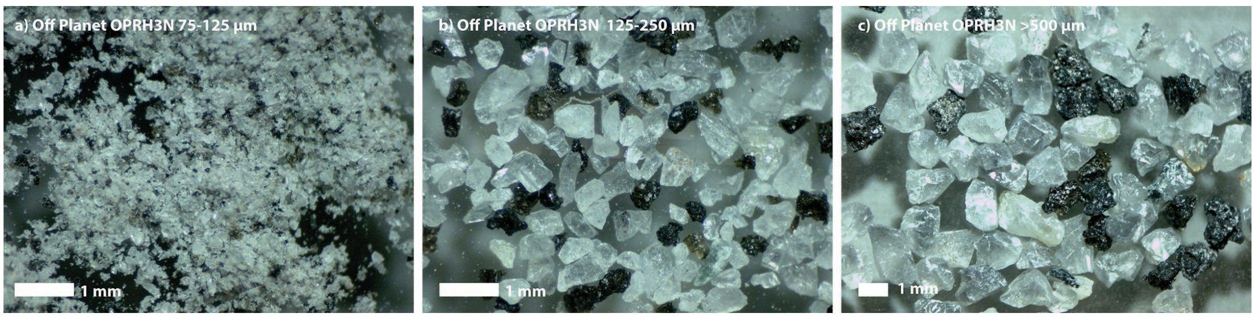

Figure 7. Off Planet Research highland simulant OPRH3N, shown at three different size fractions. The light particles are anorthosite and the dark particles are basaltic cinder.

The mare simulants include OPRL2N (90% basaltic cinder, 10% anorthosite) and OPRL2NT, which also includes ilmenite (77% basaltic cinder, 8.6% anorthosite, 14.4% ilmenite) to mimic high-titanium mare materials. Here we examined only OPRL2N (Fig. 8), we did not receive a sample of OPRL2NT.

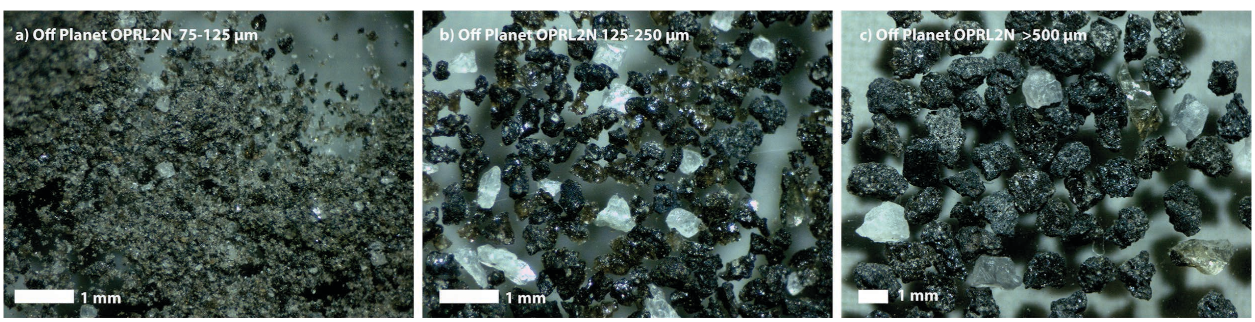

Figure 8. Off Planet Research mare simulant OPRL2N, a low-titanium mare basalt analog. The dark particles are basaltic cinder, light particles are anorthosite.

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 highland agglutinate simulant created from OPRH3N (Fig. 9) and the mare agglutinate simulant created from OPRL2N (Fig. 10) do appear to have glassy portions of each particle binding together smaller lithic fragments. The glass is most obvious as approximately spherical globules attached to the agglutinate particles.

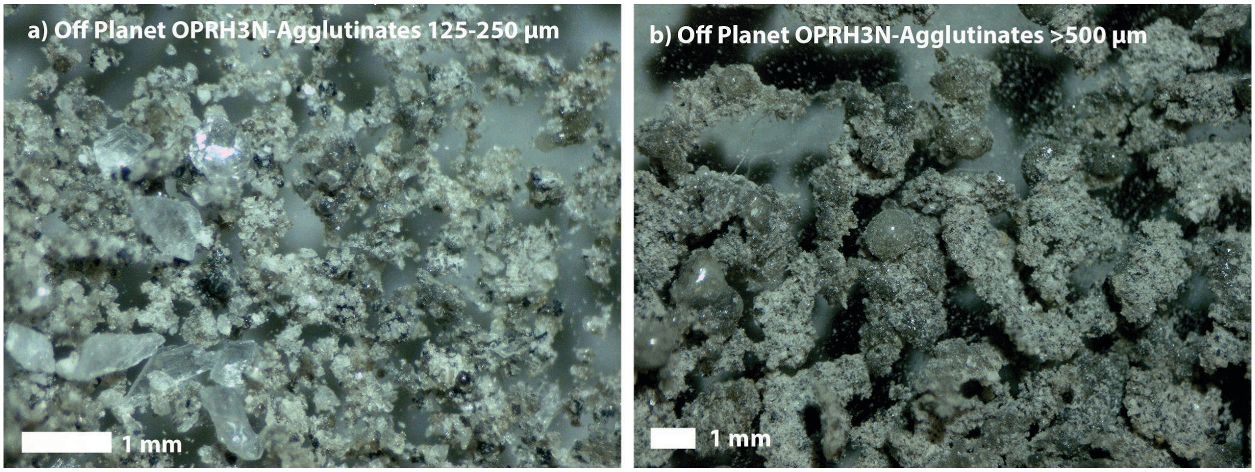

Figure 9. Off Planet Research lunar highland agglutinate simulants (created from OPRH3N) shown at two size fractions.

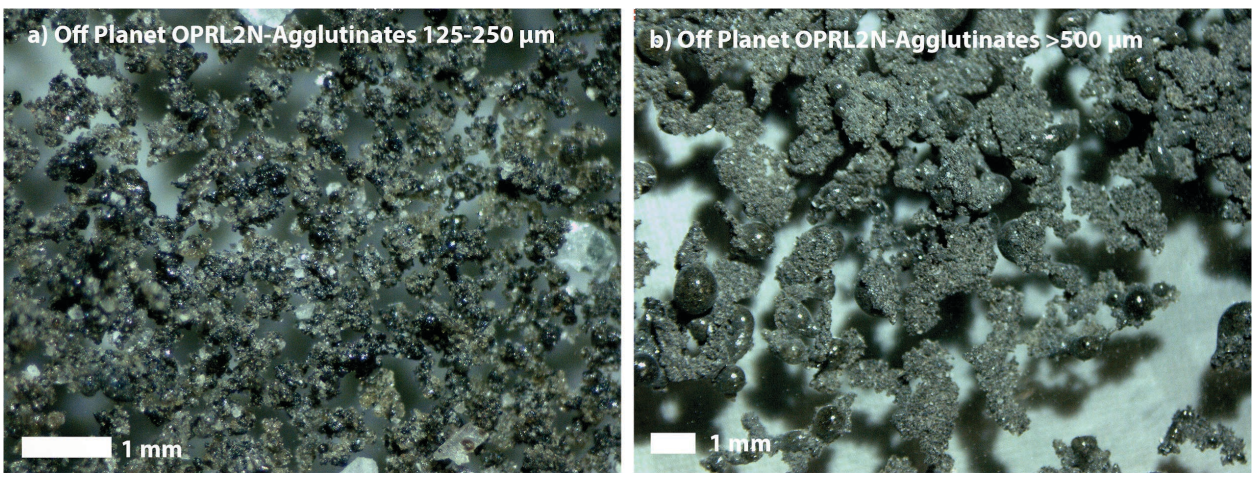

Figure 10. Off Planet Research lunar mare agglutinate simulants (created from OPRL2N) shown at two size fractions.

Unique among the three 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 experiments conducted on them, at the Off Planet Research facilities. Researchers at Off Planet Research have proposed to the National Science Foundation to make this process more portable in the future. No nanophase iron is included in the Off Planet simulants.

4.3 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 moderate degree of elongation. However, the simulant particles may be somewhat less elongated (have higher aspect ratios) than the true 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.

The simulated agglutinates display morphological variation among the different particle size fractions that we examined in the optical microscope: the largest fragments appeared "flattened" or more two-dimensional (platy) than true lunar agglutinates (Fig. 8b), and the 125–250 µm size fraction included a larger share of non-agglutinates (plagioclase grains) (Fig. 8a). The mare agglutinate simulants also showed a "flattened" shape at the largest particle sizes (Fig. 9b) and appeared to have a substantial glass component with fewer non-agglutinate particles. Both agglutinate simulants appeared to have a large components of finer grains on much of the surface, even after an ethanol wash (see Fig. 8b, 9b).

4.4 Particle Size Distribution

Table 2 (above) reports the D(50) particle-size values for the Off Planet highland and mare simulants that we tested. The Off Planet simulants fall at 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)).

After our particle size analyses were complete, a representative from Off Planet Research stated that the samples that they provided to us were part of a "rapid response" portfolio of simulants, not their "scientific grade" of simulants. Because Off Planet Research sieves each component and then mixes them by mass to match the desired particle size distribution, the size distribution can be tailored to user needs.

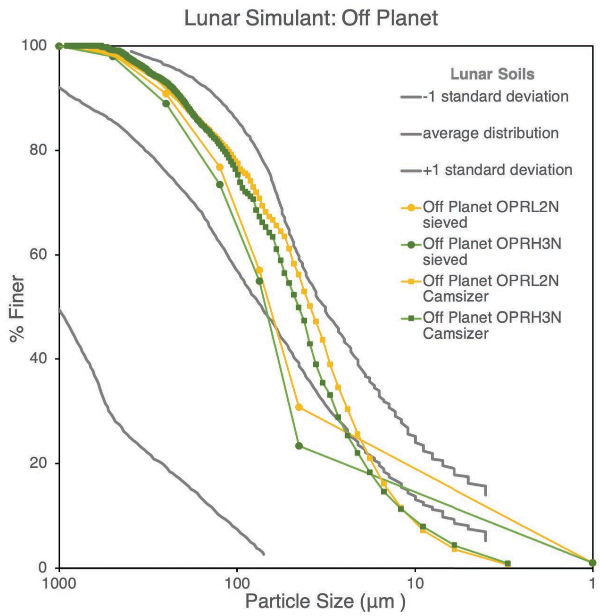

Fig. 10. Cumulative particle size distribution of Off Planet Research highland and mare simulants in comparison to Apollo samples.

An analysis of the particle size distribution of Off Planet Research agglutinates is not included here, though the data was collected, because representatives from the company stated that the agglutinate samples they provided were not intended to mimic the lunar agglutinate particle size distribution. However, they did note that “the agglutinates can be milled and sifted so that their particle size distribution will follow the same curve as the simulants, or can be otherwise customized for the client’s needs and budget.”

4.5 Composition

Our initial compositional analysis of the mare and highland simulants confirms the approximate proportions of anorthosite and basalt stated by Off Planet (Fig. 12). The samples that we analyzed show a general compositional match to Apollo lunar regolith samples (Fig. 5), though both have 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. The mare simulant also has a lower abundance of iron than typical lunar mare basalts, though these results should be confirmed with additional analyses.

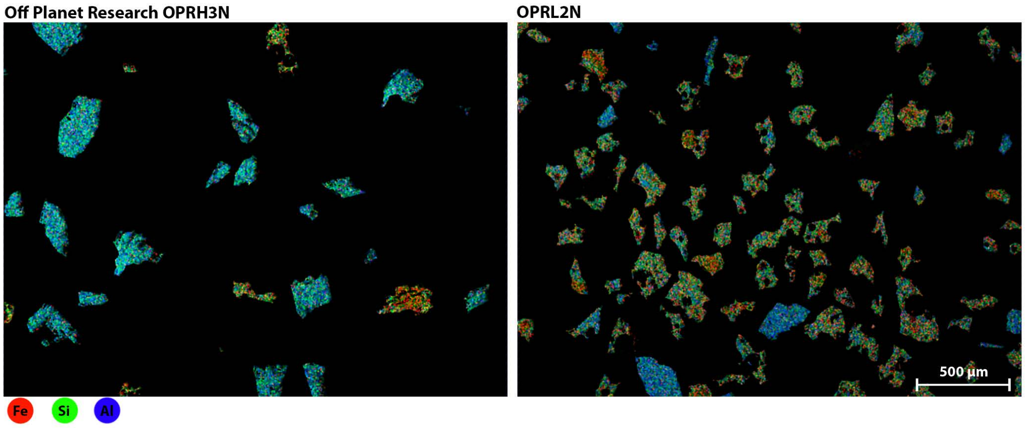

Figure 12. EDS elemental maps of Off Planet Research highland simulant OPRH3N (left) and mare simulant OPRL2N (right), with Fe, Si, and Al displayed in red, green, and blue, respectively. Green/red particles are basaltic fragments and blue particles are plagioclase.

We did not analyze the composition of the Off Planet agglutinates because they are created from the other simulants. However, further work should follow up to assess the glass and lithic clast abundance within these samples, as well as vesicularity.

4.6 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 and that given sufficient notice, one metric ton of the lunar mare and highland simulants could be delivered within eight weeks (the icy regolith simulant is produced in more limited quantities). If agglutinates need to be added to the simulant, the delivery time would increase to approximately 10 weeks. Because current orders are in the range of tens of kilograms, scaling up significantly would require the purchase of additional equipment to increase production and rate and ensure delivery date.

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 to its intended use.

5. Outward Technologies

5.1 Company Background

Outward Technologies (formerly Blueshift) is a small for-profit business in the Denver, Colorado area. The company currently has 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, and they are continuing to apply for 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.

5.2 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. The simulated agglutinates have thus far been produced from two different feedstocks, JSC-1A and the Exolith LHS-1, for mare and highland, respectively, but Outward Technologies states that they can vary the feedstock based on user needs. Simulated agglutinates can then be mixed with the feedstock from which they were created (e.g., Exolith LHS-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.

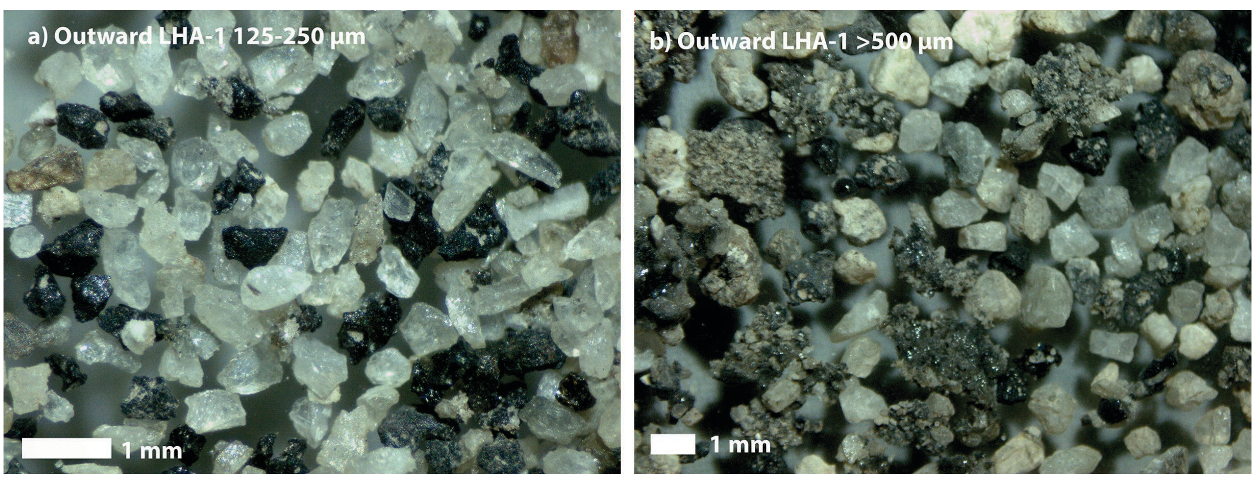

Figure 13. Outward Technologies highland agglutinate simulant LHA-1, shown at two particle size fractions.

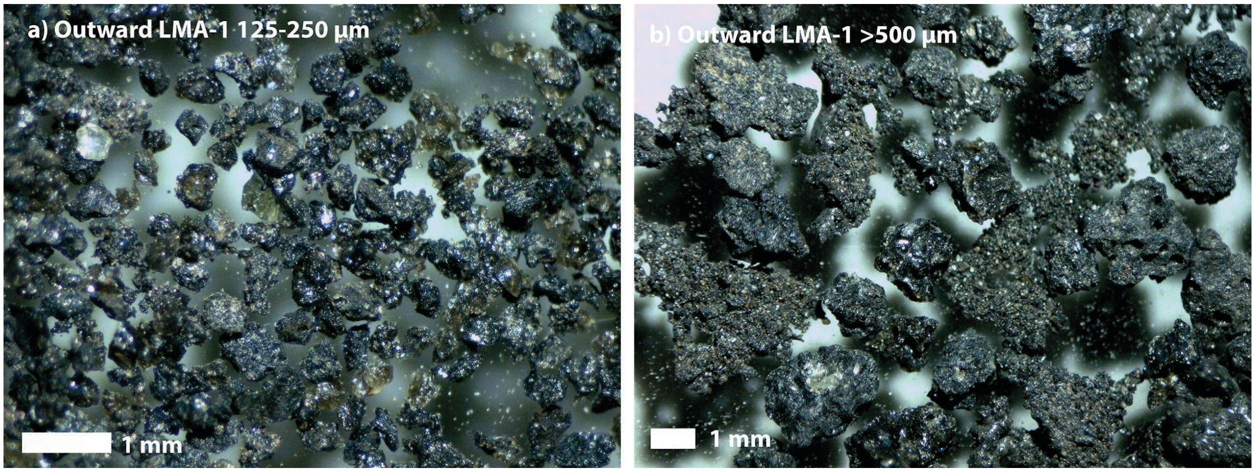

Figure 14. Outward Technologies mare agglutinate simulant LMA-1, shown at two particle size fractions.

5.3 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. 13) 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 largest size fraction (>500 µm; Fig. 13b) includes more agglutinate particles, but their overall abundance is still low (less than ~25%). The mare agglutinates appear to have a larger fraction of agglutinate-like particles, however further analysis is required to determine their glass/mineral clast ratio and vesicularity.

5.4 Particle Size Distribution

Data for the particle size distribution of the agglutinate simulants was collected but is not included here To our knowledge 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 of the Outward agglutinate simulants as observed in the optical microscope and SEM.

5.5 Composition

The composition of the Outward Technologies agglutinates is dependent on the starting feedstock, which can be varied according to user needs.

5.6 Supply Chain and Quality Control

Thus far, Outward Technologies has produced ~4 lb. of simulated agglutinates (two batches of mare simulant and two batches of highland simulant), though their founder and principal scientist, Ryan Garvey stated that by March they could ramp up for large-volume production (e.g., 1 metric ton). 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). Right now, the batch process is estimated to be 60–80% efficient (e.g., can create 60-80% agglutinates per batch). They are currently applying for NSF funding to scale up production, and scaling up depends on being able to demonstrate that there is a need for large volumes of agglutinates. With a scaled-up, continuous generation process, they estimate that production would be closer to 90% efficient.

Outward Technologies focuses on mineralogy, morphology, and strength of agglutinates in simulant design and fabrication. Currently, no characterization is done of the agglutinates outside a visual morphology inspection and sieving, however, because their in-house analysis capabilities are limited to a qualitative inspection by binocular microscope. All of the four batches of agglutinates currently produced exhibit similar morphologies. Grain size is controlled by the amount of time the material is melted and fused, and can only be roughly controlled, at present. They have fledgling partnerships in place with researchers at the Colorado School of Mines and Texas A&M to provide characterization of future simulants for quality control and for customer information. This will likely be offered as a service for simulated agglutinates in the future, but will increase the cost of the simulant. The company is open to feedback from stakeholders and customers, and they are happy to modify processes to meet customer needs.

6. Other Simulants

One additional company, 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 such as quartz, muscovite, and calcite, this bulk GreenSpar material could be an inexpensive option for some applications.

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).

7. Comparisons and Evaluations

7.1 Lunar Highland Simulants (Non-Agglutinate Fraction)

Figure 15 provides a comparison of the lunar highland simulants produced by Off Planet and Exolith are shown in comparison to Apollo 16 sample 62231, from which the majority of agglutinates have been manually removed (Denevi et al., 2020). The most striking difference is the overall reflectance. This is a mature regolith sample, and though the agglutinates have been largely removed, the majority of regolith grains have been altered by space weathering such that their surfaces have rims containing nanophase iron, which lowers their overall reflectance (e.g., Lucey et al., 2006). Additionally, whereas the simulants are a binary mixture of anorthosite and mafic minerals/lithic clasts, much of the Apollo 16 sample consists of fragments of breccias and more noritic lithic fragments, such that the mafic components are more intimately mixed. Though we note these differences, for most applications, it is unlikely that either will have a substantial impact on the effectiveness of the simulants for most uses.

The differences between the Exolith and Off Planet highland simulants include the amount of basaltic cinder mixed into the sample (24 vs. 20 wt.%, respectively), the anorthosite used (Stillwater vs. Shawmere, with the Shawmere providing a better match in terms of An#), and the particle size distribution (different, but both within one standard deviation of the mean for lunar soils). All of these differences are minor, and where they may be important for some applications (e.g., sodium abundance, nanophase iron), both are found to be lacking and without an easy remedy (terrestrial plagioclase with sodium content similar to lunar plagioclase is rare; nanophase iron is difficult to produce). Thus we find that both the Exolith and the Off Planet highland simulants are likely to be acceptable to the majority of users. Both highland simulants can also be customized to some extent, depending on user needs.

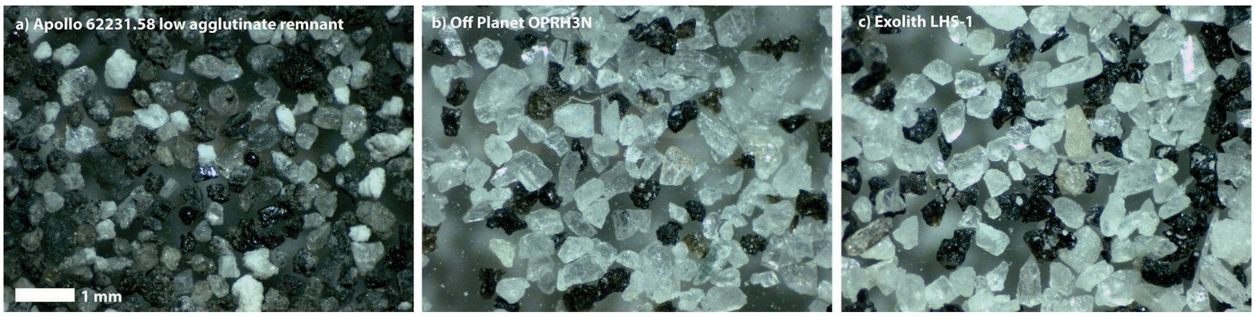

Figure 15. A comparison of a) the low-agglutinate remnant of Apollo 16 sample 62231; b) the Off Planet Research OPRH3N lunar highland simulant; and c) the Exolith LHS-1 lunar highland simulant. Each has been sieved to 125–250 µm.

7.2 Lunar Mare Simulants (Non-Agglutinate Fraction)

The mare simulants from Off Planet and Exolith are shown in comparison to the low-agglutinate remnant from Apollo 15 sample 15041 (Denevi et al., 2020; Fig. 16). Here the Off Planet simulant provides a closer match to the color and reflectance of the Apollo 15 sample because it is a combination of two lithologies, basalt and anorthosite, whereas the Exolith sample is largely a mixture of minerals (pyroxene, plagioclase, olivine, ilmenite, and basalt). Again, this difference is unlikely to be of consequence for most studies.

The major-element compositional differences between the two simulants and lunar soils again include sodium, with a higher Na_2O in the simulants compared to the lunar soils, a higher MgO content in the Exolith sample, and a lower FeO abundance in both simulants. These results should be confirmed with additional microprobe analysis, but the differences in FeO abundance would potentially be of concern for some uses (e.g., oxygen extraction; Cilliers et al., 2020; Lomax et al., 2020).

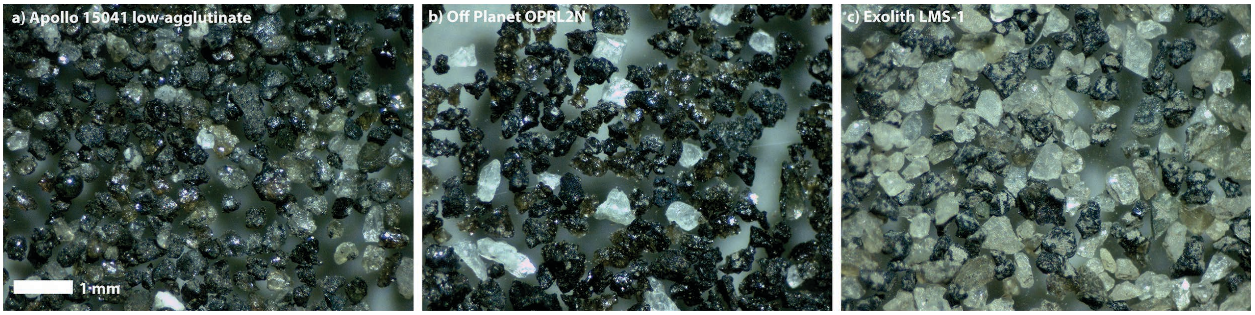

Figure 16. A comparison of a) the low-agglutinate remnant of Apollo 15 sample 15041; b) the Off Planet Research OPRL2N lunar mare simulant; and c) the Exolith LMS-1 lunar mare simulant. Each has been sieved to 125–250 µm.

7.3 Agglutinate Simulants

Further work is required to make a confident recommendation on the agglutinate simulants. Neither the Off Planet nor the Outward Technologies highland agglutinate simulant (Fig. 17) is fully agglutinated; some fraction of mineral and lithic fragments remain, though their abundance is substantially lower in the Off Planet sample. The low albedo and input feedstock (largely basaltic cinders) of the mare agglutinate simulants makes it difficult to determine if these particles are truly glass-bound lithic and mineral fragments like lunar agglutinates, or if they provide additional fidelity to lunar soils beyond using basaltic cinders alone. An initial look at agglutinate grain mounts in SEM images (Fig. 19) suggests that the highland agglutinate simulants do not show the same vesicular nature as lunar highland agglutinates, and while the mare agglutinates are vesicular, this may again be a feature of the starting material. Further analyses and an assessment of the driving use cases are warranted to determine if the addition of these agglutinate simulants would provide benefits for testing of lunar surface technologies.

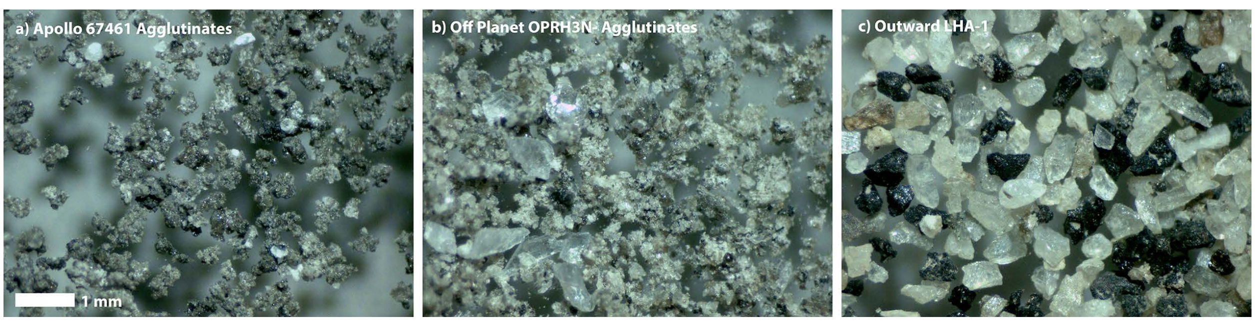

Figure 17. A comparison of a) agglutinates separated from Apollo 16 sample 67461 (Denevi et al., 2020); b) Off Planet Research OPRH3N highland agglutinate simulant; and c) the Outward LHA-1 lunar highland agglutinate simulant. Each has been sieved to 125–250 µm.

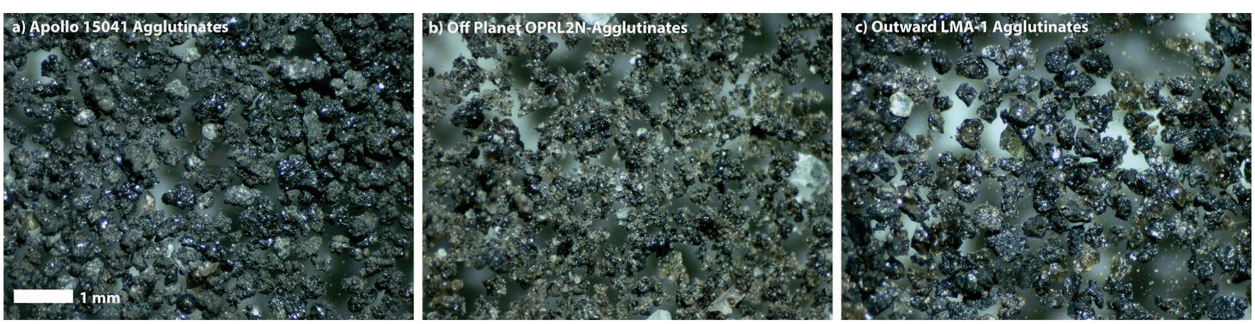

Figure 18. A comparison of a) agglutinates separated from Apollo 15 sample 15041 (Denevi et al., 2020); b) Off

Planet Research OPRL2N mare agglutinate simulant; and c) the Outward LMA-1 lunar mare agglutinate simulant. Each has been sieved to 125–250 µm.

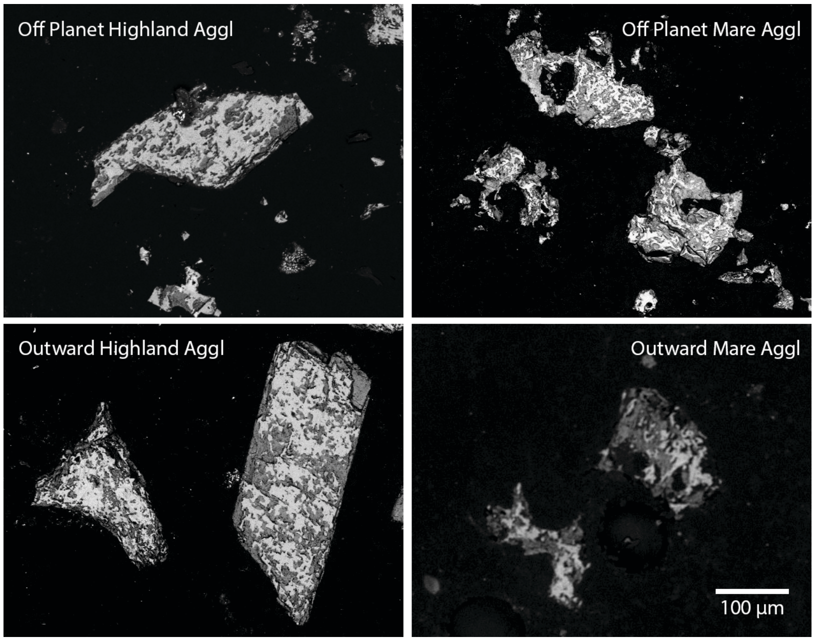

Figure 19. SEM images of agglutinate simulants. Scale bar at lower right applies to all panels.

7.4 Suitability for Testing of 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, and Outward Technologies for use in oxygen production (Table 3). 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 3, 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). See Sections 7.1–7.3 and 8 for further details.

Table 3. Comparison of selected regolith characteristics for each simulant examined in terms of their suitability for testing of oxygen extraction technology.

Important Regolith Characteristics (Oxygen Extraction)		Value[1]	Highlands Analog			Mare Analog		
			Exolith	Off Planet Research	Outward Tech.	Exolith	Off Planet Research	Outward Tech.
			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	Yellow	Yellow	N/A	Yellow	Yellow	N/A
	Mineralogy	High	Green	Green		Green	Green	
Grain Characteristics	Shape	High	Green	Green		Green	Green	
	Size Dist.	High	Yellow	Green		Green	Green	
Agglutinate Characteristics	Glassiness	High	N/A	TBD	Red	N/A	TBD	TBD
	Shape	High		Green	Red		Green	Green
Implanted Solar Particles		High	Red	Red	N/A	Red	Red	N/A
Reactivity		Medium	Red	Red		Red	Red	
Reflectivity		Medium	TBD	TBD		TBD	TBD	
Nanophase Fe		Low	Red	Red		Red	Red	
Magnetic Properties		Low	Red	Red		Red	Red	
Emissivity		Low	TBD	TBD		TBD	TBD	

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

8. 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, at a minimum, 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 for that matter 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. As lunar surface technologies progress, there should be ongoing coordinated analyses on the effects of these distinctive properties on the test and demonstration results.

These caveats stated, it is likely that simulants from the CLASS Exolith Lab (in combination with agglutinates from Outward Technologies or Off Planet Research when needed) or from Off Planet Research 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 and particle morphology, and have the flexibility to adapt to user needs for a site-dependent composition. Where the Exolith and Off Planet simulants are lacking (e.g., Table 3), there is no easy remedy. For example, one of the major differences in composition is the more sodic plagioclase in the simulants, but 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 Exolith and Off Planet, a choice between these suppliers may come down to availability (supply chain), consistency and quality control, and cost. Both companies are likely to be able to meet supply chain needs. 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 minimal quality control, and our results suggest some variations in particle size and composition may exist from batch to batch. Off Planet Research does employ rigorous quality control, including analysis of particle size and chemistry. Exolith and Outward Technologies both state a willingness to provide further verification and testing of simulants prior to delivery, but acknowledge that this will increase the cost and require additional time before delivery.

9. Further Characterization

This discussion is derived from conversations with representatives of each simulant provider, the data that they provided, conference publications, and our analysis of obtained samples of each lunar soil/agglutinate simulant available from Exolith, Off Planet Research, and Outward Technologies. Further chemical assessments such as microprobe analyses and XRD should follow for specific applications as they arise, and metrics for the assessment of the fidelity of chemical composition have been developed (e.g., Chang and Ann, 2019). 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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