2021-2022 LSIC Simulants Assessment Reports: Community Resource

September 2023 LSWG Speaker Series

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What is Lunar Regolith?
- A complex mixture of particles that covers the lunar surface
  - Crystalline rock fragments
    - Highland - Anorthosite (>90% Plagioclase)
    - Mare - Basalt
  - Mineral fragments
    - Limited compositional range
    - Rims tend to be amorphous and contain nanophase Fe$^0$ (npFe$^0$)
  - Breccias
  - Agglutinates
  - Glass
- Unique particle sizes and shapes!
  - Avg. particle size = ~70 microns
  - Elongated particles, subangular to angular
LSII | Lunar Regolith Simulants

• An approximation of Lunar Regolith
  - Anorthite
    - White Mountain Anorthosite (aka GreenSpar) from Kangerlussuaq, Greenland (Avg. An83; Gruener et al., 2020)
    - Shawmere Anorthosite Complex in Ontario, Canada (Avg. An78; Battler and Spray, 2009)
  - Basalt (providers often use glassy basalts to mimic the glass content)
    - (Previously) Black Lava Rock from Pebble Junction
    - San Francisco volcanic field (Arizona) basaltic cinder
  - Ilmenite (FeTiO$_3$)

• Missing unique components of Lunar Regolith
  - Agglutinates
    - Some providers are making them in the lab
  - Nanophase Fe$^0$ metal
  - Amorphous mineral rims
Methods
Lunar Simulants – Composition & Particle Size/Shape (2020, 2021)

**Bulk Composition (XRF, SEM)**

**Mineralogy (XRD, SEM)**

**Particle Size Distribution (Sieve, Camsizer)**

**Particle Shape (Camsizer)**

- **X-ray Fluorescence (XRF)**
- **Scanning Electron Microscope (SEM)** EDS-enabled
- **X-ray Diffraction (XRD)**
- **Camsizer**
- **Sieve Pans**

**LSII Lunar Simulants Assessment Results (2020-2022)**

Aspect Ratio = $a / b$
Lunar Simulants – Particle Size Distribution Methodology (2020, 2021)

• Particle Size Distribution - Sieving
  - Exolith Lab, Off Planet Research, and Outward Technologies
  - 6 particle size fractions (<45 µm, 45–75 µm, 75–125 µm, 125–250 µm*, 250–500 µm, and >500 µm)
    - *Used for EDS analysis
    - ~2.0 – 2.5 g per sample was sieved
      - Smaller sieves and smaller sample amounts
  - Dry and wet sieving

[Images of sieves and particle size fractions]
Lunar Simulants – Camsizer Methodology (2020, 2021)

- **Camsizer Particle Shape and Sizes**
  - Retsch Technology, Camsizer X2
  - 3 aliquots (100mg) of each sample

- **Provides**
  - Particle sizes in 3 um bins (0-3, 3-6, etc.)
  - Aspect Ratio and Sphericity (aka shape)
  - Velocity profile

Aspect

Increasing elongation

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>Complexity</th>
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<tbody>
<tr>
<td>0.4</td>
<td>1.0</td>
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<tr>
<td>0.5</td>
<td>1.1</td>
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<tr>
<td>0.48</td>
<td>1.3</td>
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Least-Square Fit Ellipse

Round

Angular

Jagged

Complexity

Exolith - Particle Size Distribution

- LHS-1 sieved
- LMS-1 sieved
- LHS-1 Camsizer
- LMS-1 Camsizer
- -1 standard deviation
- Apollo average
- +1 standard deviation
Lunar Simulants – SEM Methodology (2020, 2021)

- **Preparation**
  - Epoxy grain mounts (20-30 mg, size fraction 125-250 µm)
  - Carbon coated

- **SEM – Scanning Electron Microscopy**
  - Hitachi TM 3000

- **EDS - Energy Dispersive X-ray Spectroscopy**
  - Bruker Quantax 70

EDS Map

Si
Fe
Al

LMA-1 Agglutinate

Si
Fe
Al

LSII Lunar Simulants Assessment Results (2020-2022)
Lunar Simulants – Geotechnical Characteristics (2022)

- **Particle Size Distribution (Sieve)**
- **Direct Shear Strength**
- **Specific Gravity**
- **Min & Max Density**

- Water pycnometry method
Lunar Simulants – Particle Size Distribution Methodology (2022)

- **Particle Size Distribution - Sieving**
  - Exolith Lab, Off Planet Research, Colorado School of Mines, Deltion Innovations, USGS/NASA
  - ASTM E11 Test Sieves
  - 6 particle size fractions
    - 500 g per sample was sieved

<table>
<thead>
<tr>
<th>ASTM E11 Opening Size</th>
<th>Particle Size (microns)</th>
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<tr>
<td>35</td>
<td>&gt;500</td>
</tr>
<tr>
<td>50</td>
<td>297-500</td>
</tr>
<tr>
<td>100</td>
<td>149-297</td>
</tr>
<tr>
<td>200</td>
<td>74-149</td>
</tr>
<tr>
<td>325</td>
<td>45-74</td>
</tr>
<tr>
<td>pan</td>
<td>&lt;45</td>
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</table>
Lunar Simulants – Min/Max Density Methodology (2022)

Measures density of uncompacted and compacted simulants/soils

• Includes cylinder, tube for sample fill, and a weight

• Minimum Density
  - Uses cylinder and tube
  - Mass comes from the simple fill

• Maximum Density
  - Uses cylinder, tube, and weight
  - Mass comes from the simple fill with weight compaction
Lunar Simulants – Specific Gravity Methodology (2022)

Measures the ratio of solid particles’ unit weight to the unit weight of water

• **Running the test:**
  - Measure flask with and without water up to defined fill line
  - Add ~75g of soil to empty flask
  - Fill flask to defined fill line with distilled water
  - Attach vacuum pump and slowly apply vacuum while swirling sample
    - This removes trapped air
  - Remove pump and weigh
  - Calculate density of soil using

\[
G_S = \frac{(M_3-M_1)}{(M_2-M_1)-(M_4-M_3)}
\]
Lunar Simulants – Direct Shear Strength Methodology (2022)

Collects strain data and plots it on a stress-strain curve (displacement in inches vs. shear force in lbs) for each confining stress

• GeoTac Digishear machine
  - applies a horizontal and vertical load

• Done under ambient conditions

• A confining stress was applied vertically to the soil
  - 500 pounds per square foot (PSF)
  - 1500 PSF
  - 3000 PSF

• Once the vertical stress was stable, a horizontal stress was applied to the upper ring
  - The machine is moving 0.1 inches per minute to a maximum displacement of 0.25 inches
Selected Results
Lunar Simulants – Particle Size & Shape (2021)

- Particle Size Distribution (PSD)
  - Sieved materials (circles)
  - Camsizer system (squares)
Lunar Simulants – Composition (2020, 2021)

• Bulk composition – XRF and SEM (Na$_2$O)

(SEM of 125-250 µm split)

Highlands Regolith Compositions

Mare Regolith Compositions

(SEM of 125-250 µm split)
Lunar Simulants – Particle Size & Shape (2022)

- Particle Size Distribution (2022)

Mare

- <74 µm
- 74-149 µm
- 149-297 µm
- 297-500 µm
- >500 µm

Highland
Lunar Simulants – Particle Size & Shape (2021)

• Particle shape – Aspect Ratio
  - 1.0 = perfect sphere
Lunar Simulants – Shear Strength (2022)

• Direct Shear Strength measurements
  - Friction angles within range measured for lunar soils
  - Cohesion exceeds that measured for lunar soils
Lunar Simulants – Specific Gravity (2022)

• Specific Gravity
  - All simulants have specific gravity values within the range observed for lunar soils
Lunar Simulants – Min & Max Density (2022)

- Minimum and Maximum Density
  - Maximum density values for all simulants fall within the range measured for lunar soils
  - Minimum density values for simulants exceed the range measured for lunar soils, except for OPRH2N (highland) and OPRL2N (mare) simulants

![Graph showing Min-Max Densities for Highland Regolith Simulants](image1)

![Graph showing Min-Max Densities for Mare Regolith Simulants](image2)
Conclusions
LSII | LSWG Considerations

• The evaluation and utility of a simulant is specific to its application
  - Melting/microwaving regolith requires high compositional fidelity
    - Difference in Na content may be important
      o Petrologic modeling suggests large differences in viscosity of the liquid produced by melting
      o Small changes in the melting temperature due to Na differences
  - Material durability studies would require high fidelity in particle shape & size
    - Lunar particles tend to be very angular and “interlock” so they have unique behavior

• Regolith simulants and even lunar regolith do not necessarily behave in the same way on Earth as they would on the Moon
  - Solar wind implants volatiles on lunar surface (reactivity, cohesive forces, etc.)
  - Nanophase Fe⁰ results in magnetic properties in lunar regolith
  - Lower confining stresses at lunar surface
    - We attempted to compare our data to only earth-based measurements on lunar regolith
LII | LSWG Considerations

- Lunar regolith simulants from current simulant providers could meet the needs of most users
  - You can add components to increase fidelity in appropriate areas
    - Synthetic Materials & Glasses
    - Psuedo-Agglutinate Simulant
    - Magnetic susceptibility materials

- For advanced (high TRL) testing, it may be wise to compare results using a simulant with and without pseudo-agglutinate simulant, and potentially even a lunar soil (in the lab or on the lunar surface).
Lunar Simulants Working Group (LSWG)

• LSWG on LSIC Webpage (under Our Work)
  - Info on APL & NASA Simulants Teams, Assessments & Databases, Pubs
  - Links to Wiki, Simulants Portal, & Simulants Survey

• LSWG Confluence Page (requires LSIC membership)
  - Space for LSIC members to share simulant information
    ▪ Annual Simulant Assessments
    ▪ Relevant Publications
  - Lunar Simulants Portal - data collected on lunar simulants, provider info, etc.
  - APL & NASA Simulants Teams
  - https://lsic-wiki.jhuapl.edu/display/LSWG/Lunar+Simulants+Working+Group+Home

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