Lunar Regolith Simulants
2021 APL Assessment

EE Monthly Meeting (May 2022)

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Lunar Regolith

• Unconsolidated material covering the lunar surface
  - Mostly a fine, gray “soil”
  - Breccia and rock fragments
  - Agglutinates
  - Pyroclastic materials (volcanic glass)

• Relevance (It’s EVERYWHERE!)
  - ISRU (volatiles, other materials)
  - Excavation and Construction (building materials, excavation processes)
  - Extreme Access (“bulk transport of lunar regolith”)
  - Extreme Environments (“endogenic factor”)

19 May 2022

NASA photo AS11-40-5877
From Lunar Sourcebook Ch. 7, Fig. 7.2
Lunar Regolith Facts

- Regolith Properties (ala Roy Christoffersen)
  - Composition - Underlying rock
    - Basalt (Fe-rich)
    - Anorthosite (Ca-rich Anorthite)
Lunar Regolith Facts

- Regolith Properties (ala Roy Christoffersen)
  - Composition - Underlying rock
    - Basalt
    - Anorthosite

- Grain size & shape
  - ~50% <31 um

From Lunar Sourcebook Ch. 7, Fig. 7.9

Liu et al. (2008) Fig. 1
Lunar Regolith Facts

• Regolith Properties (ala Roy Christoffersen)
  - Composition - Underlying rock
    ▪ Basalt
    ▪ Anorthosite

• Grain size & shape
  - ~50% <31 um

• Unique components
  - Agglutinates
  - Nanophase Fe metal (npFe$^0$)
  - Amorphous mineral rims (especially Plagioclase)
Lunar Regolith Simulants

• An approximation of Lunar Regolith
  - Composed of Terrestrial Rocks
    ▪ Compositional differences
      o Terr. Plag. is more Na-rich
      o Terr. Basalt may not be as Fe-rich
    ▪ Exposed to water at the surface
      o Weathered surfaces, oxidized
  - Missing unique components
    ▪ No Agglutinates
    ▪ No nanophase Fe$^0$ metal
    ▪ Mineral rims tend to be crystalline
  - We do have similar rock types
    ▪ Breccia and rock fragments
    ▪ Pyroclastic materials (volcanic glass)
Highland Simulants: 3 Grain Sizes

Highland Pseudo-agglutinate

Outward Technologies
Highland Agglutinate Simulant LHA-1

Exolith LHS-1
75-125 μm
125-250 μm
>500 μm

1 mm 1 mm 2 mm

Off Planet Research OPRH3N
75-125 μm
125-250 μm
>500 μm

1 mm 1 mm 2 mm

CSM-LHT-1
75-125 μm
125-250 μm
>500 μm

1 mm 1 mm 2 mm

(farside)
Mare Simulants: 3 Grain Sizes

Mare Pseudo-agglutinate

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Outward Technologies

Mare Agglutinate Simulant LMA-1

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Exolith LMS-1

75-125 µm

125-250 µm

>500 µm

1 mm

2 mm

Off Planet Research OPRL2N

75-125 µm

125-250 µm

>500 µm

1 mm

2 mm

CSM-LMT-1

75-125 µm

125-250 µm

>500 µm

1 mm

2 mm
Particle Size and Shape

• Particle size bins of 3 μm for all samples (i.e., 0-3 μm, 3-6 μm, etc.)

• Particle size distribution (PSD) results are D(10), D(50), and D(90)
  - e.g., D(50) = 75 μm indicates that 50% of the particles are <75 μm in diameter
  - Should be equivalent to weight percent derived from sieve analysis

• Camsizer system also reports several shape parameters for each bin size, including
  - Aspect ratio (i.e., AR = b/a; perfect sphere = 1)
  - Sphericity (i.e., perfect sphere = 1; aka complexity)

Figure after Liu et al. (2008)
Particle Shape: Aspect Ratio

• Simulant aspect ratios are higher (more rounded) than Apollo regolith
Particle Size: Median vs. Mode

- Simulant D(50) values overlap with lunar regolith median particle size

*Mean value, no medians reported for Apollo 16 or 17
Particle Size: Distribution (PSD)

- PSD for simulants plot within one standard deviation of Apollo regolith PSD average, although simulant PSD have steeper slope
Composition

Bulk Chemistry (XRF)
- Portable Thermo Scientific Niton XL3t 980 analyzer
  - Repeated analyses on 5 splits of bulk material
  - Detection limits (Mg, Na)

Minerology (XRD)
- Panalytical Empyrean diffraction cabinet using Reference Intensity Ratio method
  - Incident x-rays are diffracted by crystalline material
  - For samples with multiple phases present, provides semi-quantitative abundances
Composition: Bulk Chemistry (Highland) - XRF

Highlands Regolith Compositions

(SEM of 125-250 µm split)
Composition: Bulk Chemistry (Mare) - XRF

(SEM of 125-250 μm split)
### Composition: Mineralogy (Highland Simulants) - XRD

<table>
<thead>
<tr>
<th>Company</th>
<th>Simulant</th>
<th>Type</th>
<th>Plagioclase</th>
<th>Olivine</th>
<th>Pyroxene</th>
<th>Groutite</th>
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<td>87</td>
<td>6.5</td>
<td>-</td>
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<td>-</td>
<td>-</td>
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<tr>
<td>CO School of Mines</td>
<td>LHT-1</td>
<td>Highland</td>
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<tr>
<td>Outward Technology</td>
<td>LHA-1</td>
<td>HL aggl</td>
<td>100</td>
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<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Phases:**
- **Plagioclase:** Labradolite (as anorthite).
- Glassy mafic rocks/minerals are not identified by XRD.
Composition: Mineralogy (Highland Simulants) - XRD

SEM Maps of 125-250 µm split*

- **R** = Fe  
- **G** = Si  
- **B** = Al

- Plagioclase = blues
- Ol/Pyx = green/orange

Apollo 16 Highland Regolith

Exolith LHS-1

Off Planet Research OPRH3N

CSM LHT-1
### Composition: Mineralogy (Mare Simulants) - XRD

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<tr>
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<td>Simulant</td>
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<td>OPRL2N</td>
<td>LMT-1</td>
<td>LMA-1</td>
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<td><strong>Type</strong></td>
<td>Mare</td>
<td>Mare</td>
<td>Mare</td>
<td>Mare aggl</td>
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<tr>
<td><strong>Plagioclase</strong></td>
<td>100</td>
<td>100</td>
<td>77(^1)</td>
<td>76(^1)</td>
</tr>
<tr>
<td><strong>Olivine</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pyroxene</strong></td>
<td>-</td>
<td>-</td>
<td>23</td>
<td>24</td>
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<tr>
<td><strong>Groutite</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^1\)Phase ID = Labradorite, (all other identified as anorthite).

Glassy mafic rocks/minerals are not identified by XRD.
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Exolith LMS-1

Off Planet Research OPRL2N

CSM LMT-1
Pseudo-Agglutinates by Outward Technologies

- **2021** OT Highland Pseudo-Agglutinate Simulant
Comparison: Lunar Highland Pseudo-Agglutinate

Apollo Regolith

a) Apollo 67461 Agglutinates

Outward Technologies Pseudo-Agglutinate

b) Outward Technologies LHA-1

1 mm

1 mm
Pseudo-Agglutinates by Outward Technologies

- **2021** OT Mare Pseudo-Agglutinate Simulant
Comparison: Lunar Mare Pseudo-Agglutinate

Apollo Regolith

Outward Technologies Pseudo-Agglutinate

a) Apollo 15041 Agglutinates

b) Outward Technologies LMA-1
2021 Assessment Conclusions

• The evaluation and utility of a simulant is specific to its application
  - e.g., Melting/microwaving regolith requires high compositional fidelity
  - e.g., Material durability studies would require high fidelity in particle shape & size

• 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 Fe$^0$ results in magnetic properties in lunar regolith
  - Lower confining stresses at lunar surface

• Lunar regolith simulants from current simulant providers could meet the needs of most users
  - You can add components – including synthetic materials – to increase fidelity in appropriate areas

• For advanced (high TRL) testing related to ISRU needs, it may be wise to compare results using a simulant with and without pseudo-agglutinates, and potentially even a lunar soil (in the lab or on the lunar surface).
Downloadable Assessment doc

• Confluence: https://lsic-wiki.jhuapl.edu
  - Lunar Simulants Working Group
  - LSWG Resource Library -> Recent Simulant Assessments
    ▪ Scroll to the bottom of the Page

• Public webpage: https://lsic.jhuapl.edu
  - Resources -> Lunar Simulants
  - Click on Assessments and Databases tab
    ▪ Click on the 2021 Lunar Simulant Assessment