Lunar Surface Innovation
CONSORTIUM

2021-2022 LSIC Simulants Assessment Reports: Community Resource

September 2023 LSWG Speaker Series

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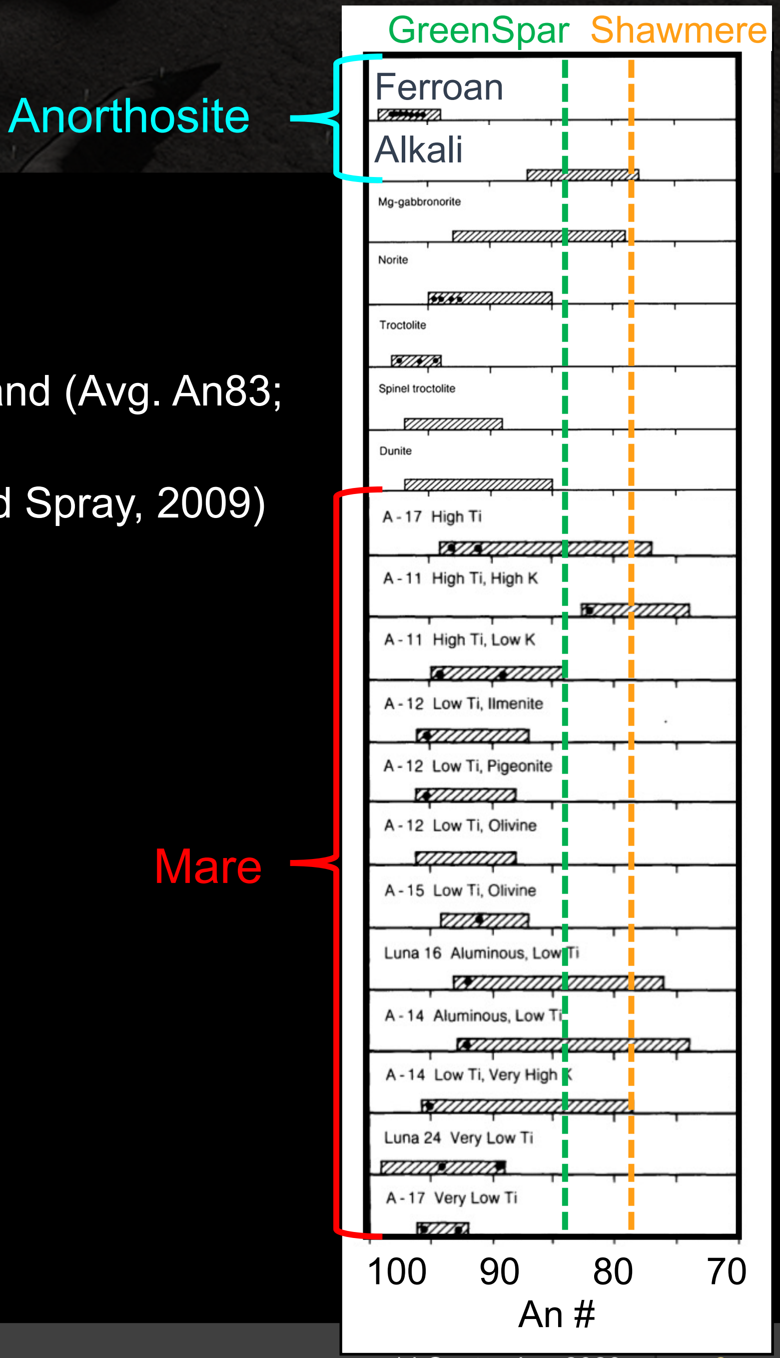
LSII | Lunar Regolith

- 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

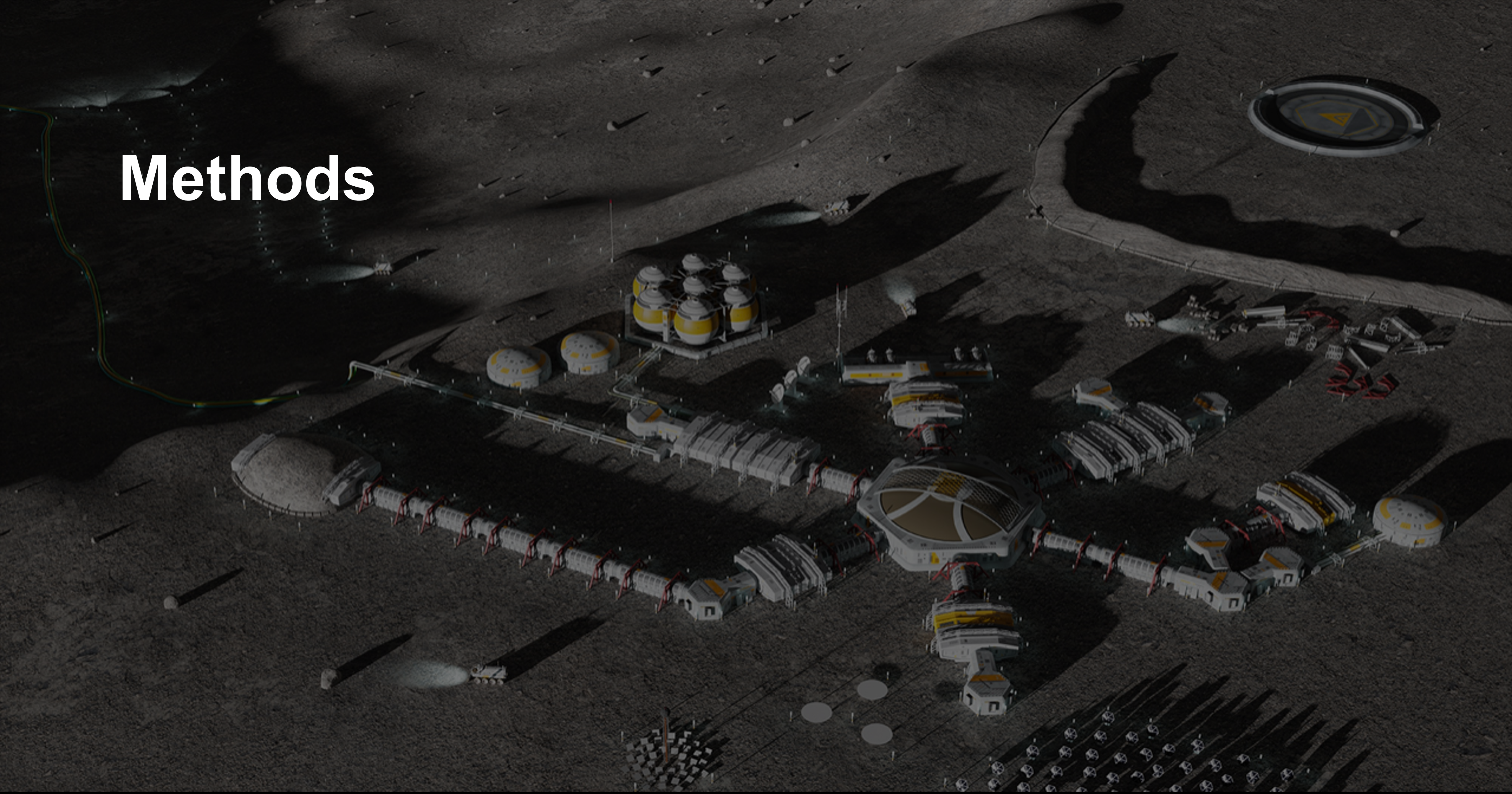
LSII | Lunar Regolith Simulants

- 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



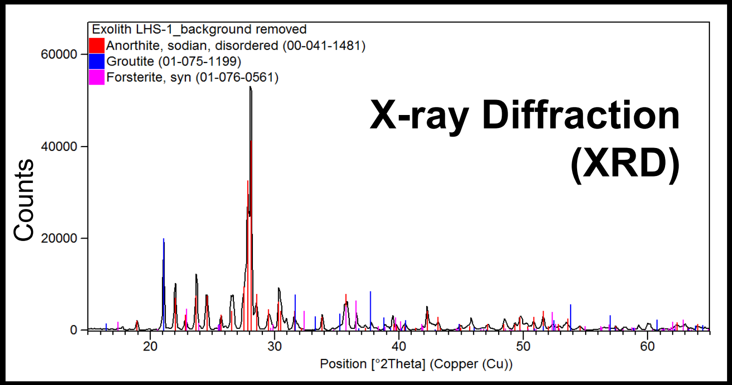
Methods

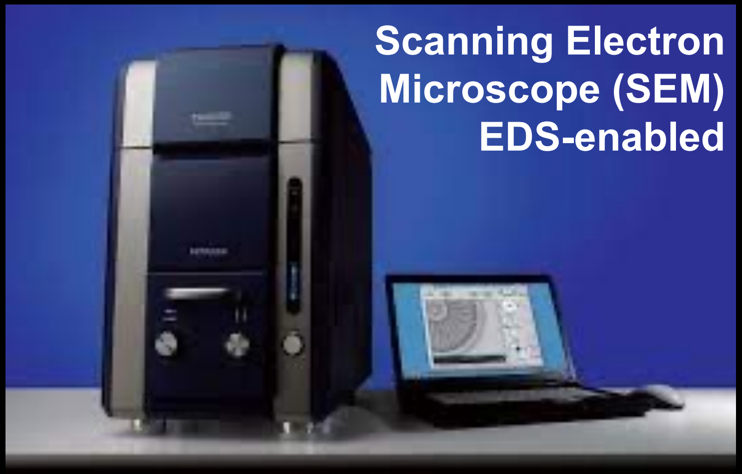


Lunar Simulants – Composition & Particle Size/Shape (2020,2021)

Bulk Composition (XRF, SEM)

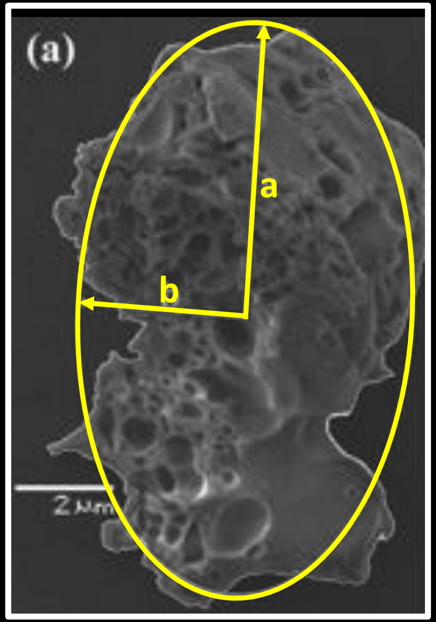
Mineralogy (XRD, SEM)





Particle Size Distribution (Sieve, Camsizer)

Particle Shape (Camsizer)



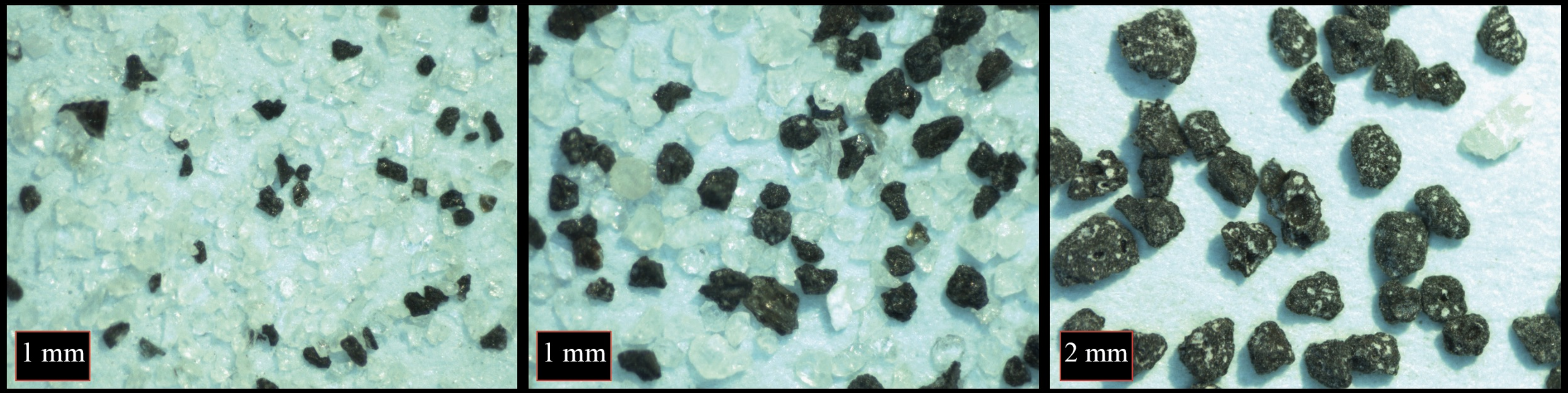
Aspect Ratio = a / b

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

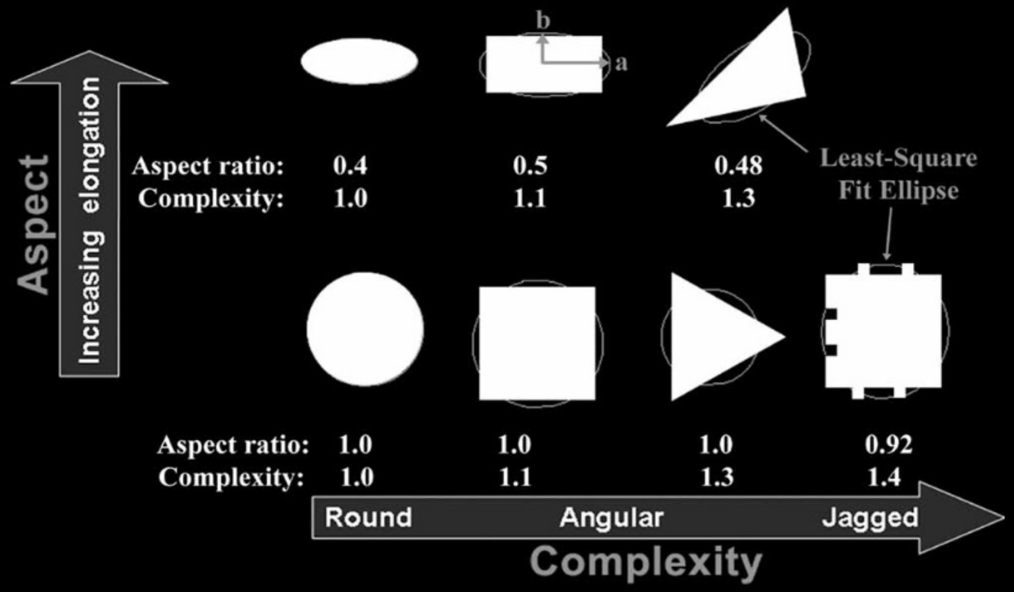
Exolith LHS-1

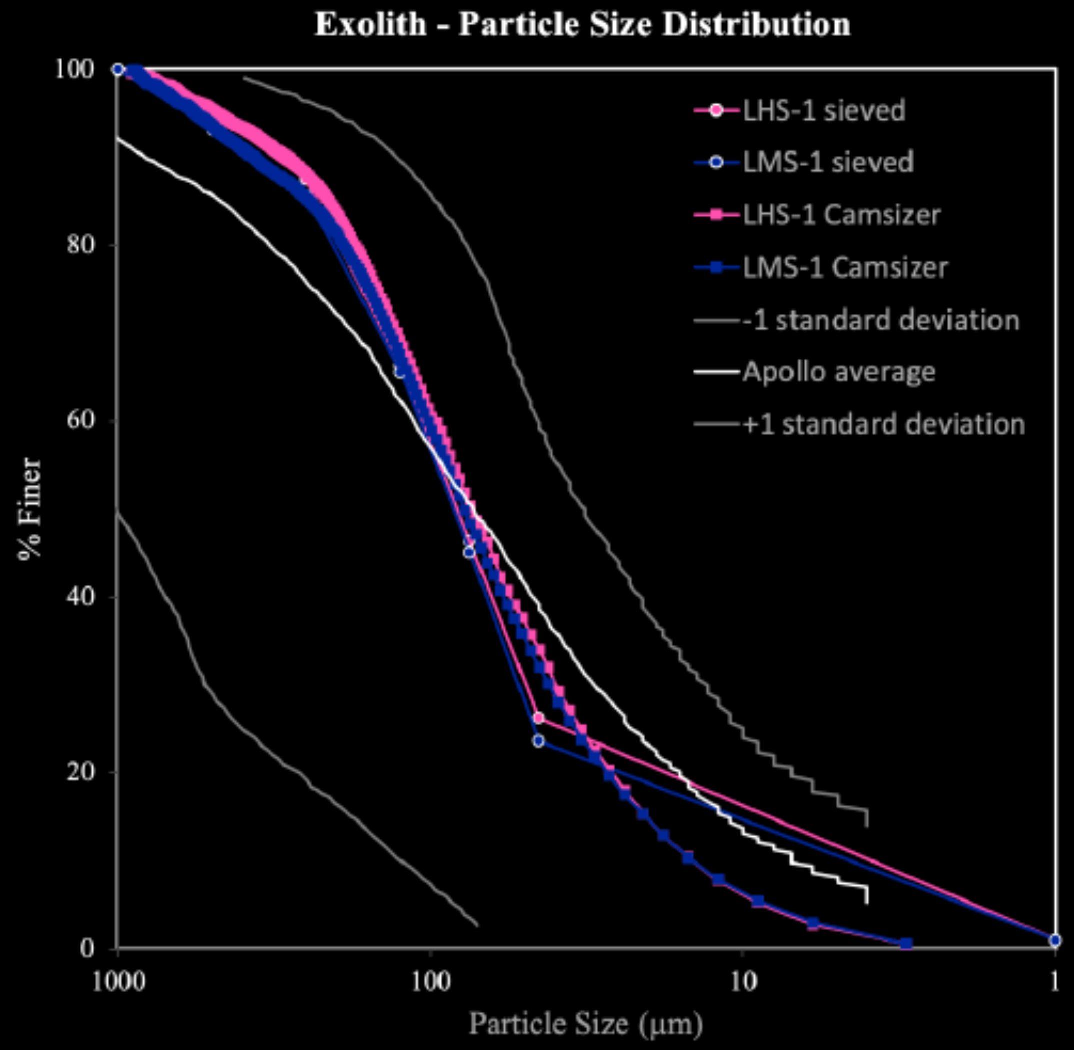
75-125 µm **125-250 µm** **>500 µm**



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



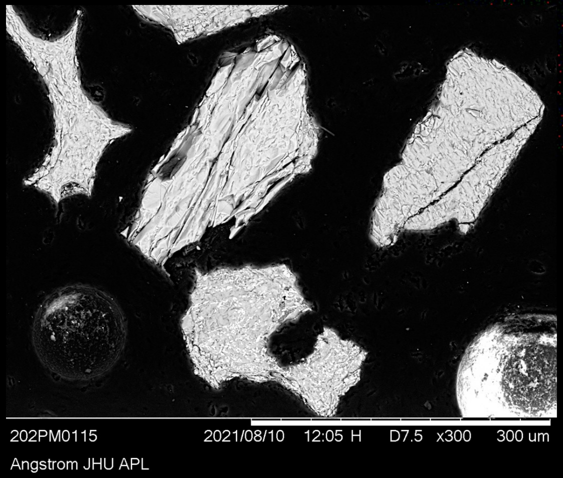


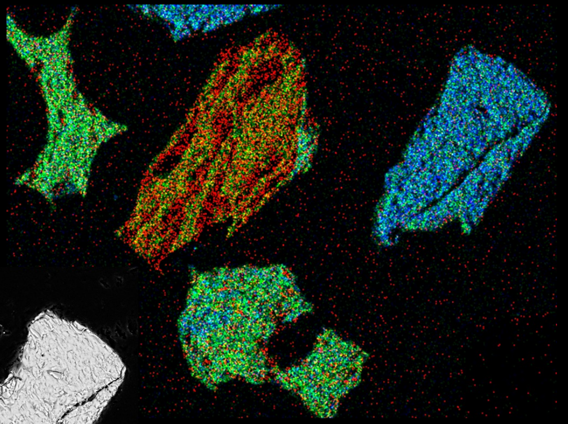
Lunar Simulants – SEM Methodology (2020, 2021)

- **Preparation**
  - Epoxy grain mounts (20-30 mg, size fraction 125-250 µm)
  - Carbon coated
- **SEM – Scanning Electron Microscopy**
  - Hitatchi TM 3000
- **EDS - Energy Dispersive X-ray Spectroscopy**
  - Bruker Quantax 70

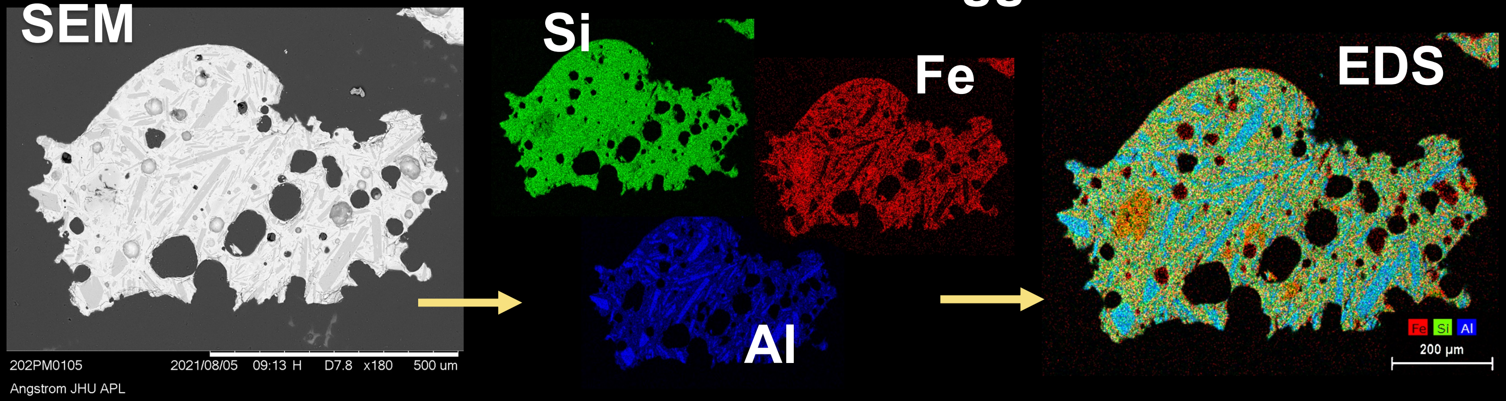
LHA-1

SEM Backscatter



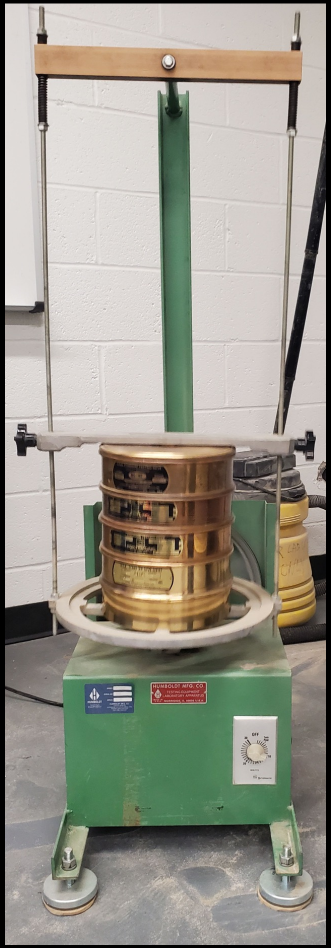


LMA-1 Agglutinate

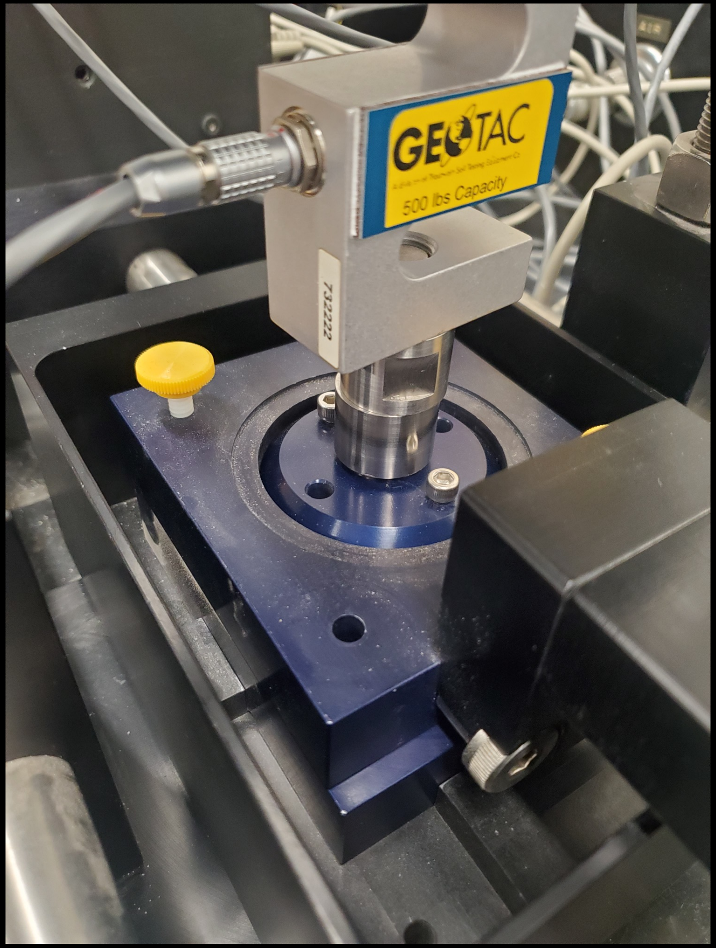


Lunar Simulants – Geotechnical Characteristics (2022)

Particle Size Distribution (Sieve)



Direct Shear Strength



Specific Gravity

Min & Max Density

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

ASTEM E11 Opening Size	Particle Size (microns)
35	>500
50	297-500
100	149-297
200	74-149
325	45-74
pan	<45

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

Cylinder/ tube

Excess material being removed after fill

Weight compaction for maximum density

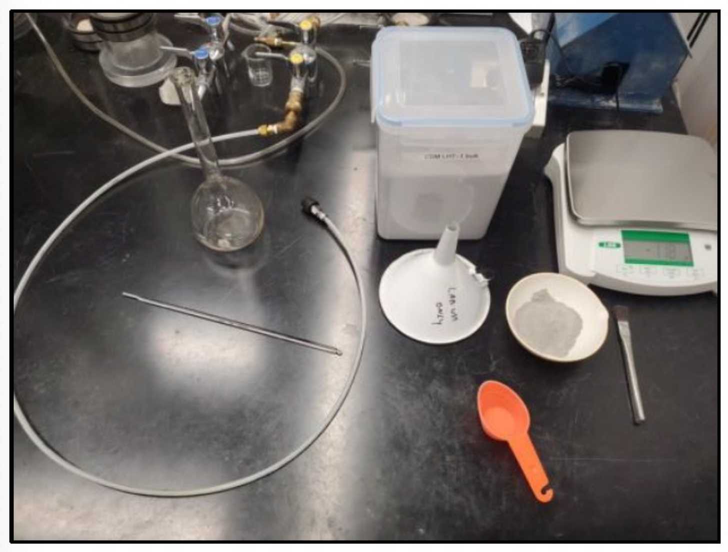
Lunar Simulants – Specific Gravity Methodology (2022)

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

$$G_S = (M_3 - M_1) / (M_2 - M_1) - (M_4 - M_3)$$

The 500 mL volumetric flask, vacuum tub hose, thermometer, funnel, and scale used to conduct the experiment

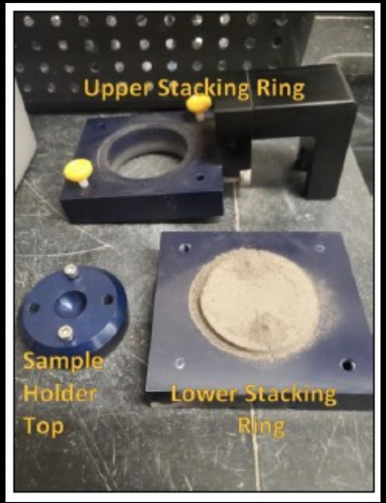


Simulant material combined with the water and sample being weighed at the end of testing

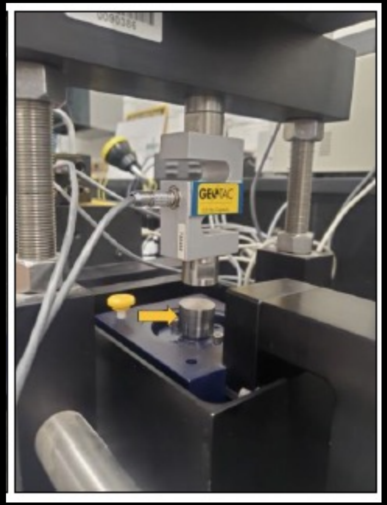
Lunar Simulants – Direct Shear Strength Methodology (2022)

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



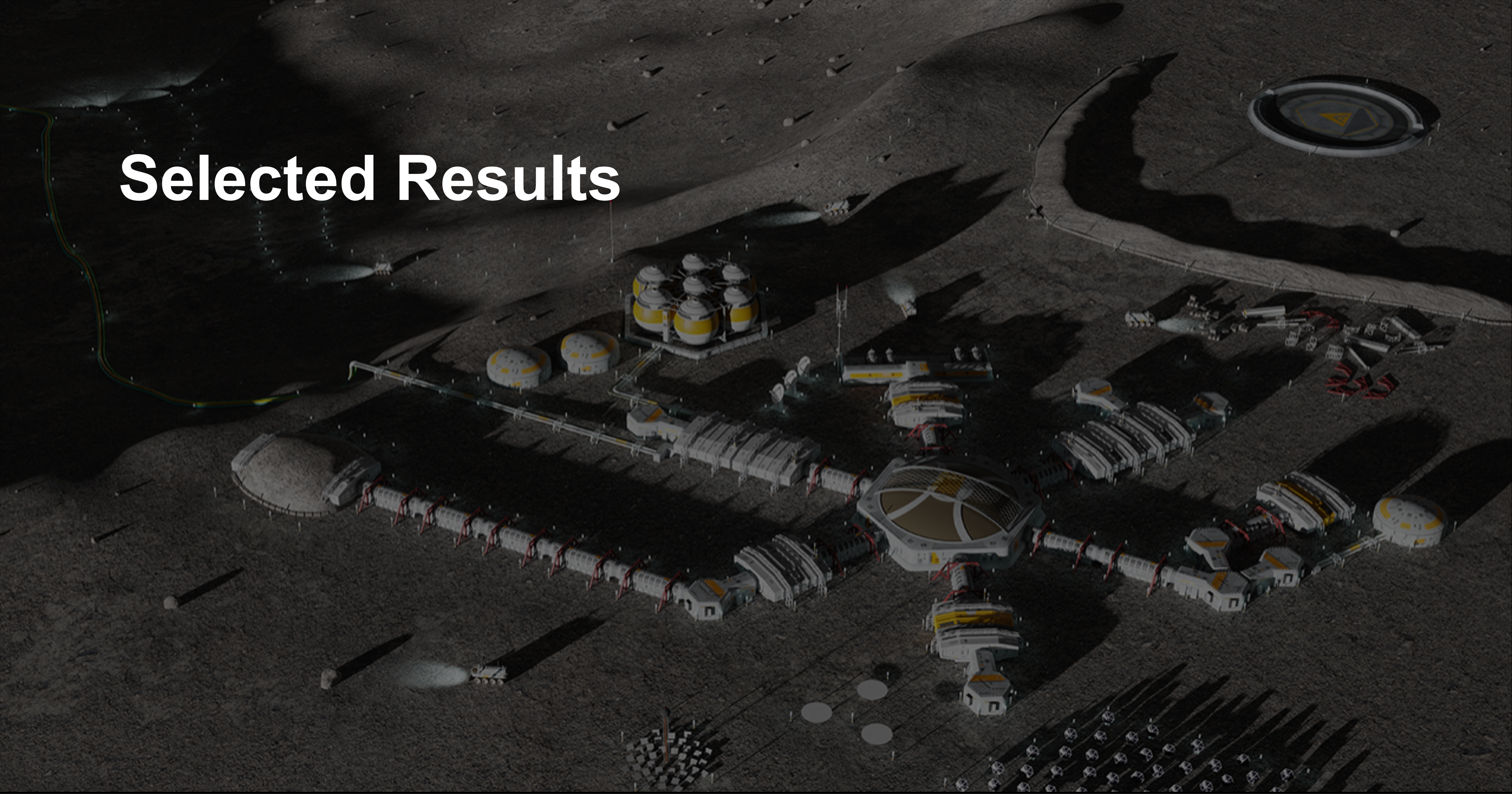
Set up



Vertical Stress

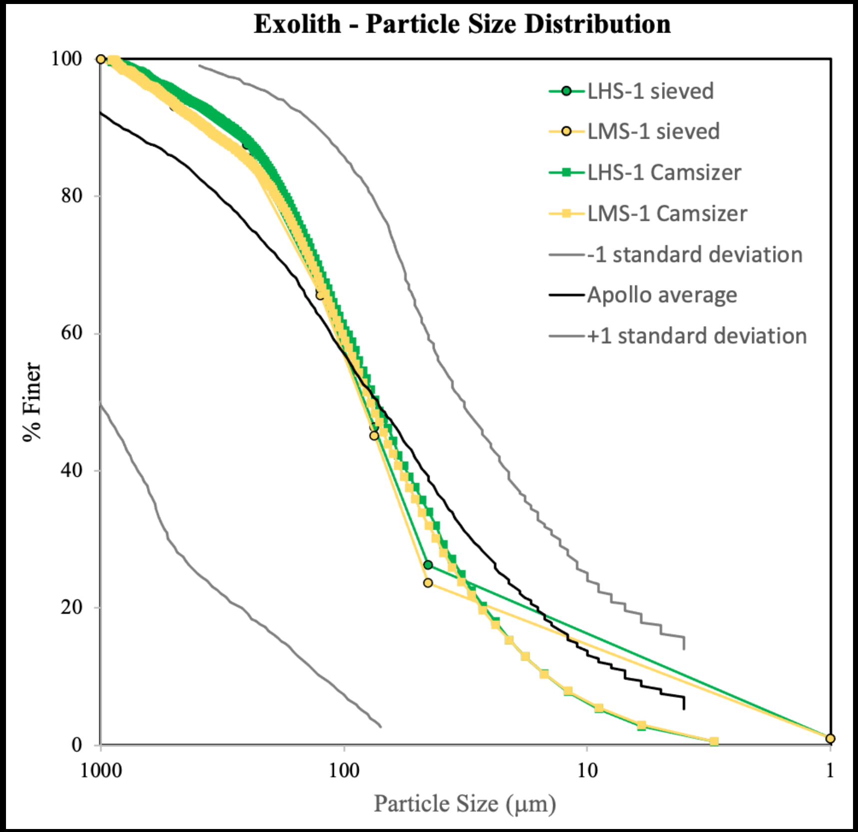
Horizontal Stress

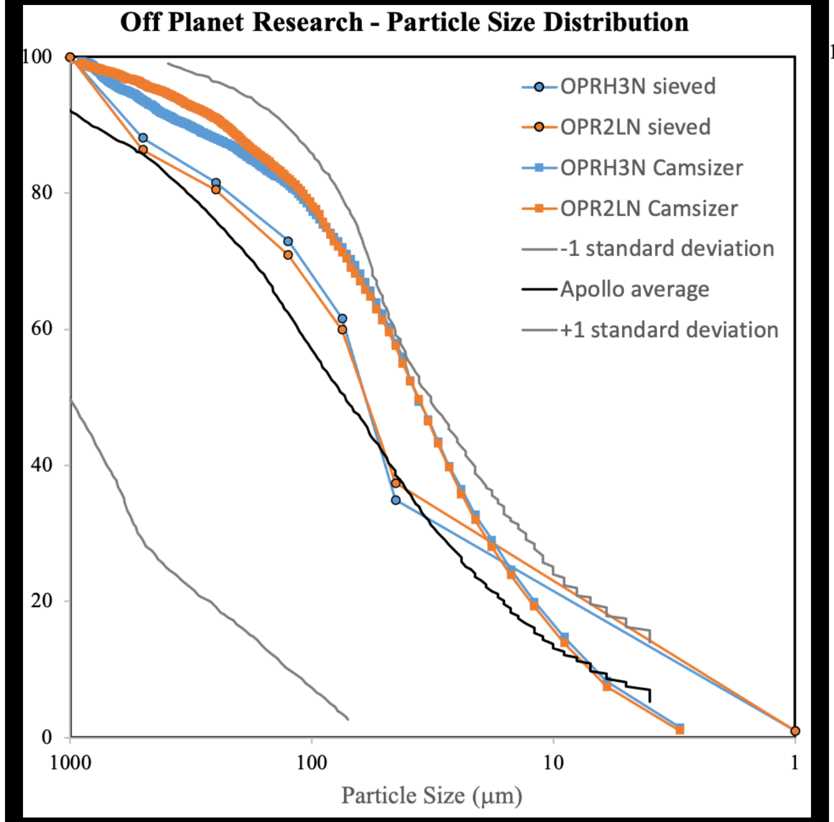
Selected Results

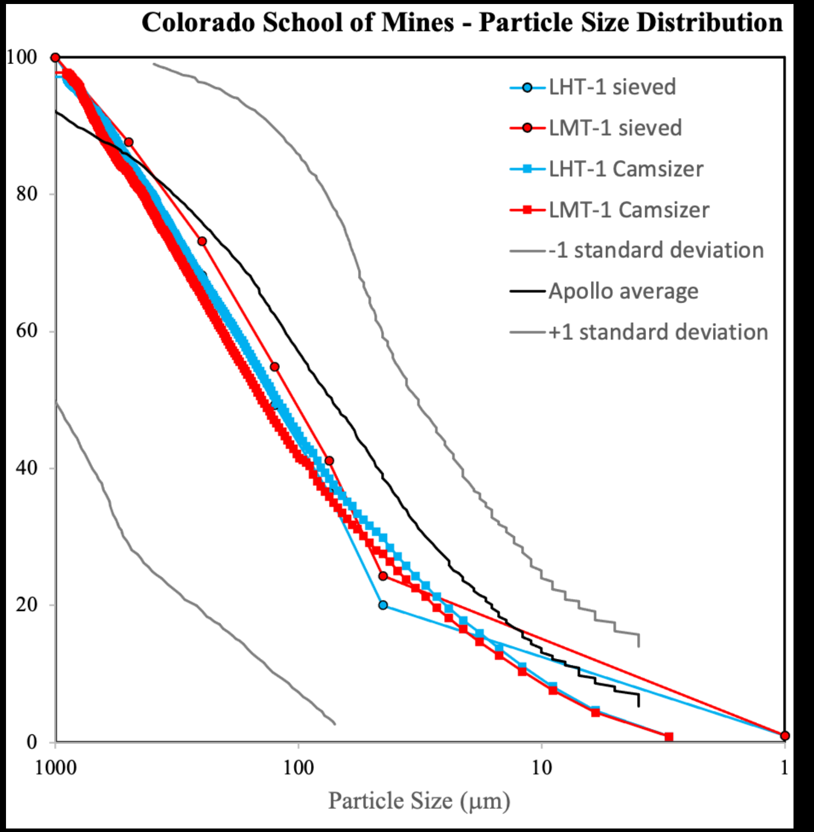


Lunar Simulants – Particle Size & Shape (2021)

- **Particle Size Distribution (PSD)**
  - Sieved materials (circles)
  - Camsizer system (squares)

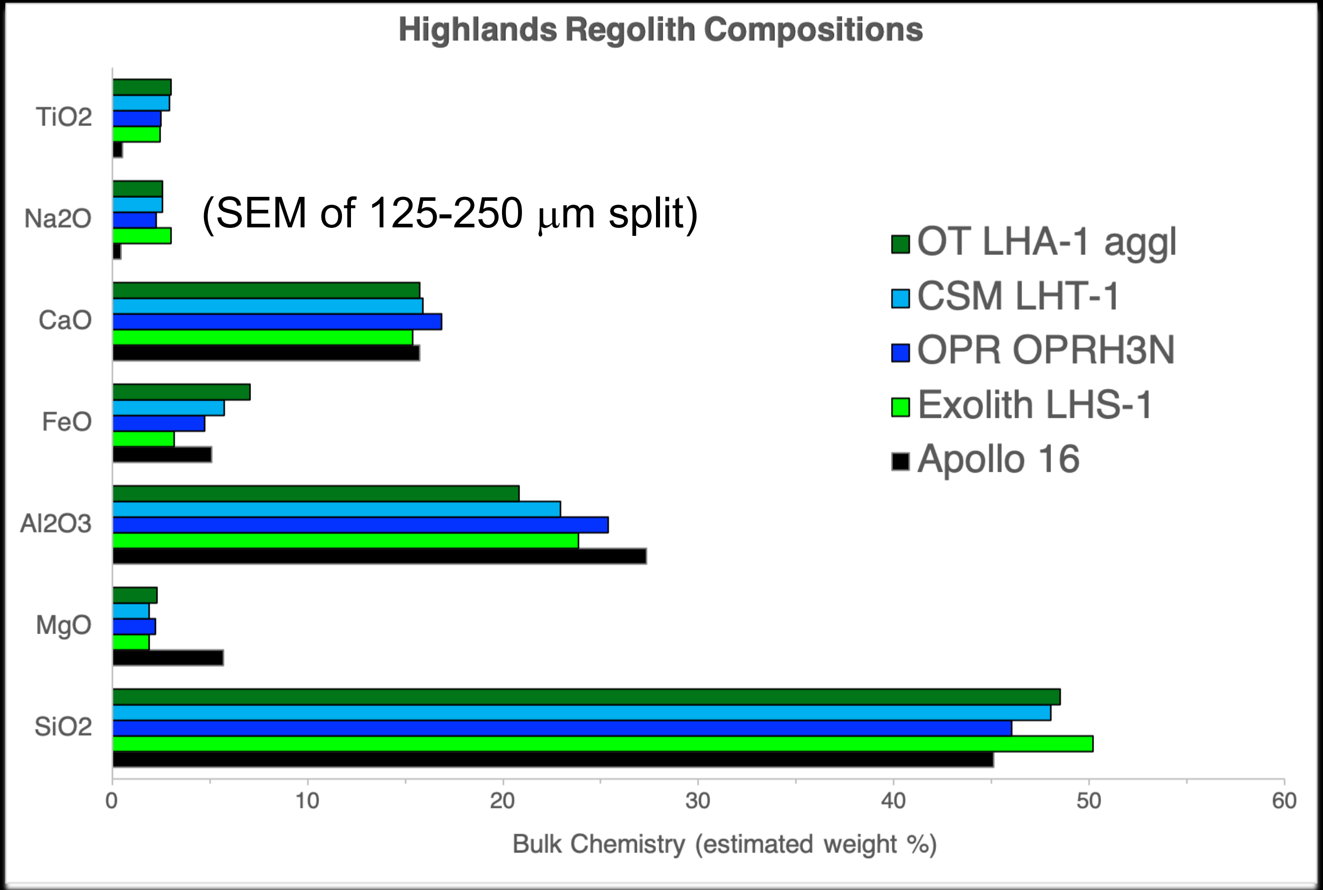


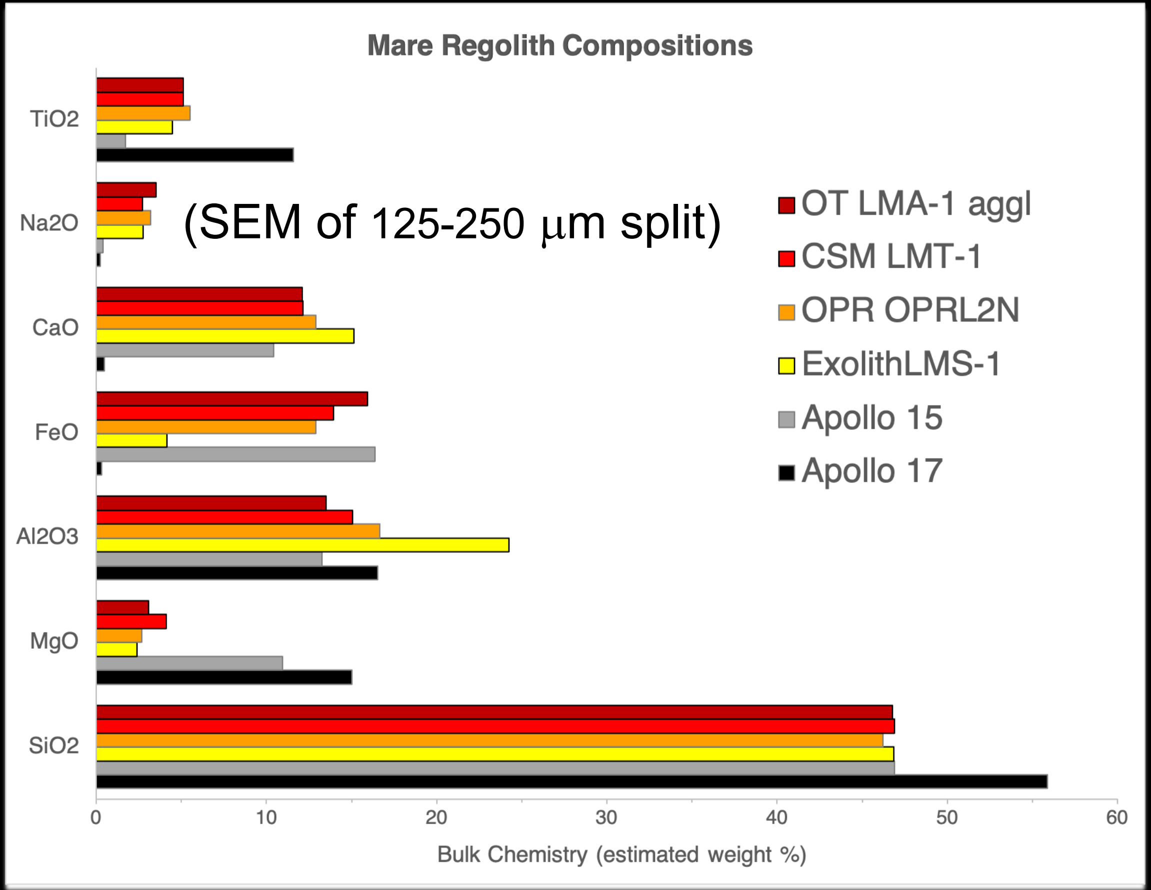




Lunar Simulants – Composition (2020, 2021)

- **Bulk composition – XRF and SEM (Na_2O)**





Lunar Simulants – Particle Size & Shape (2022)

- **Particle Size Distribution (2022)**

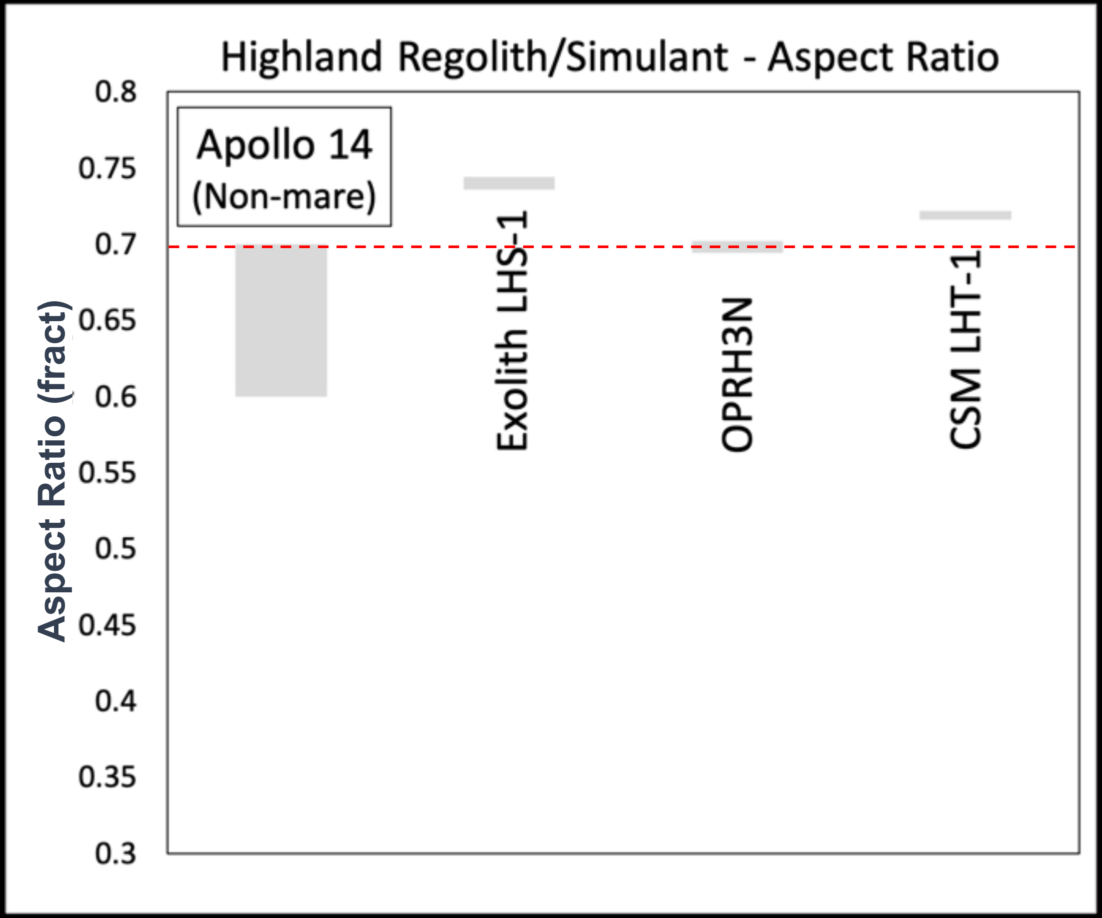
Mare

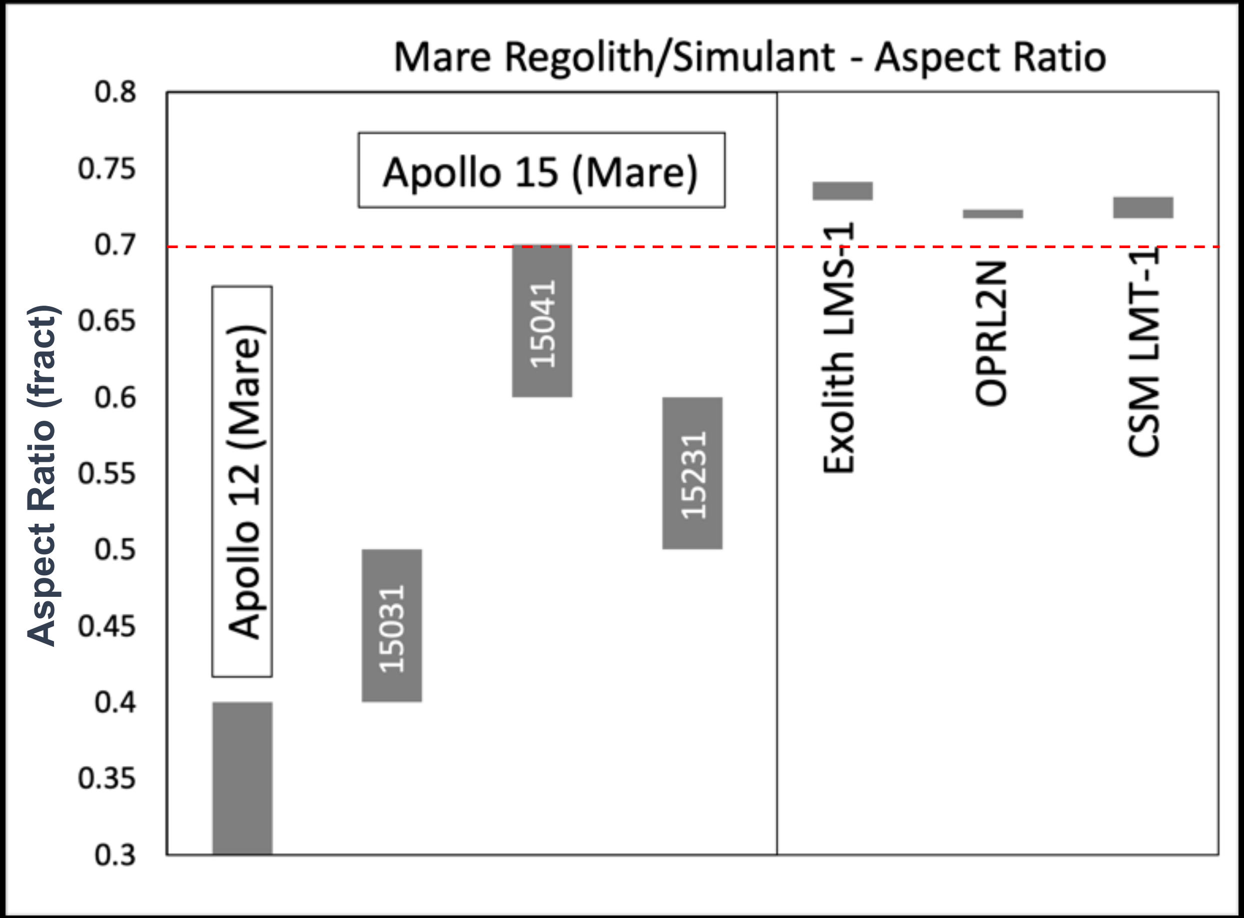
<74µm | 74-149 µm | 149-297µm | 297-500 µm | >500 µm

Highland

Lunar Simulants – Particle Size & Shape (2021)

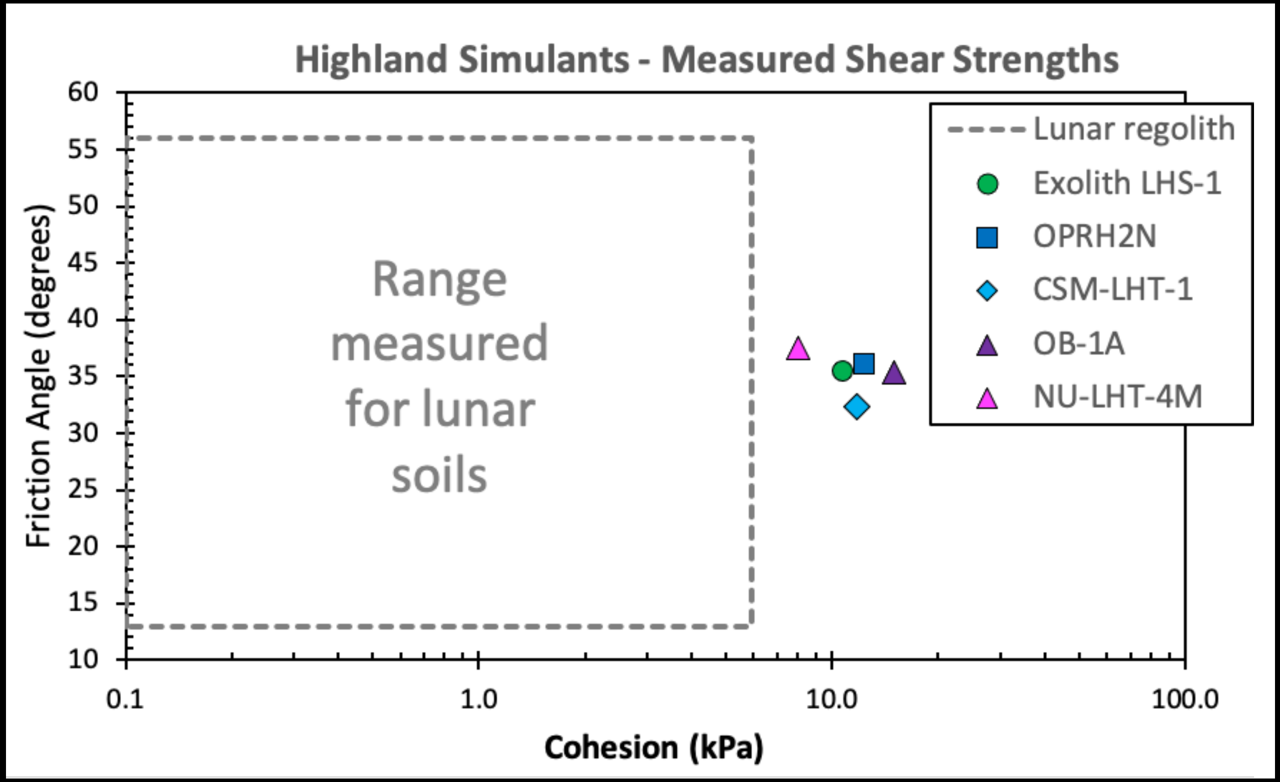
- **Particle shape – Aspect Ratio**
  - 1.0 = perfect sphere

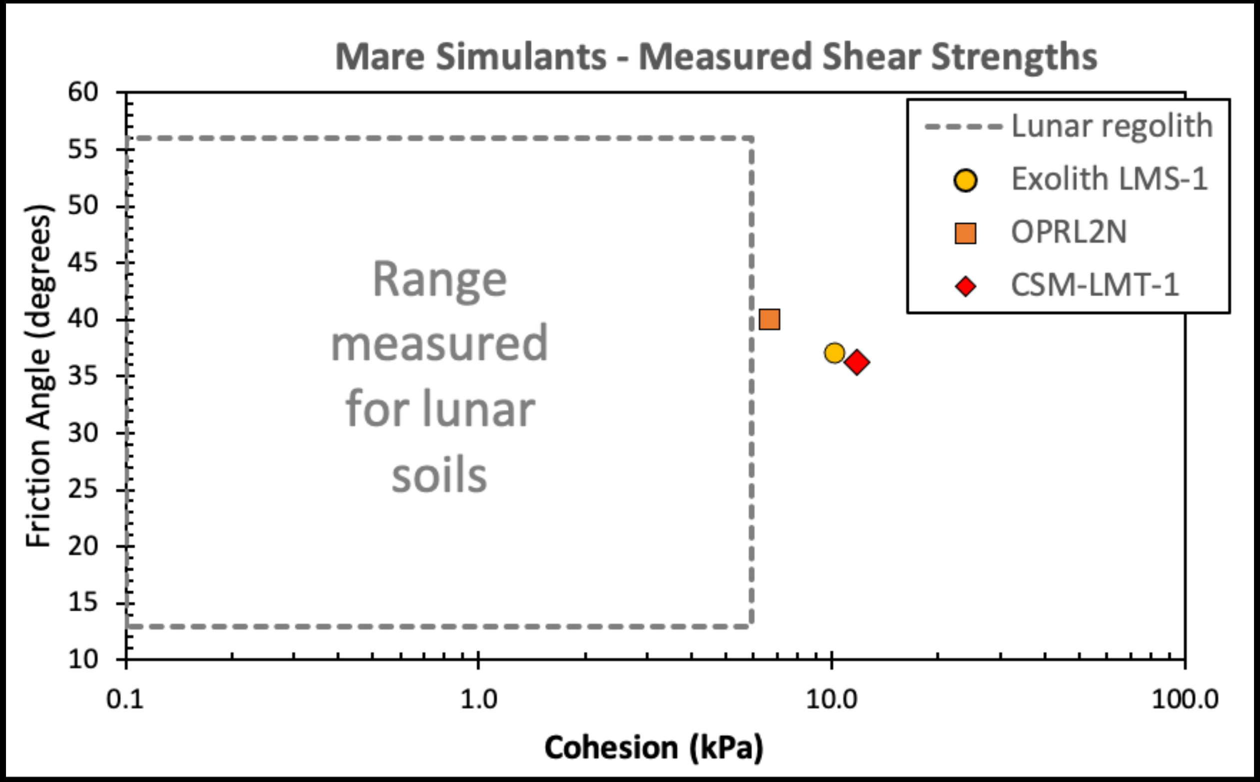




Lunar Simulants – Shear Strength (2022)

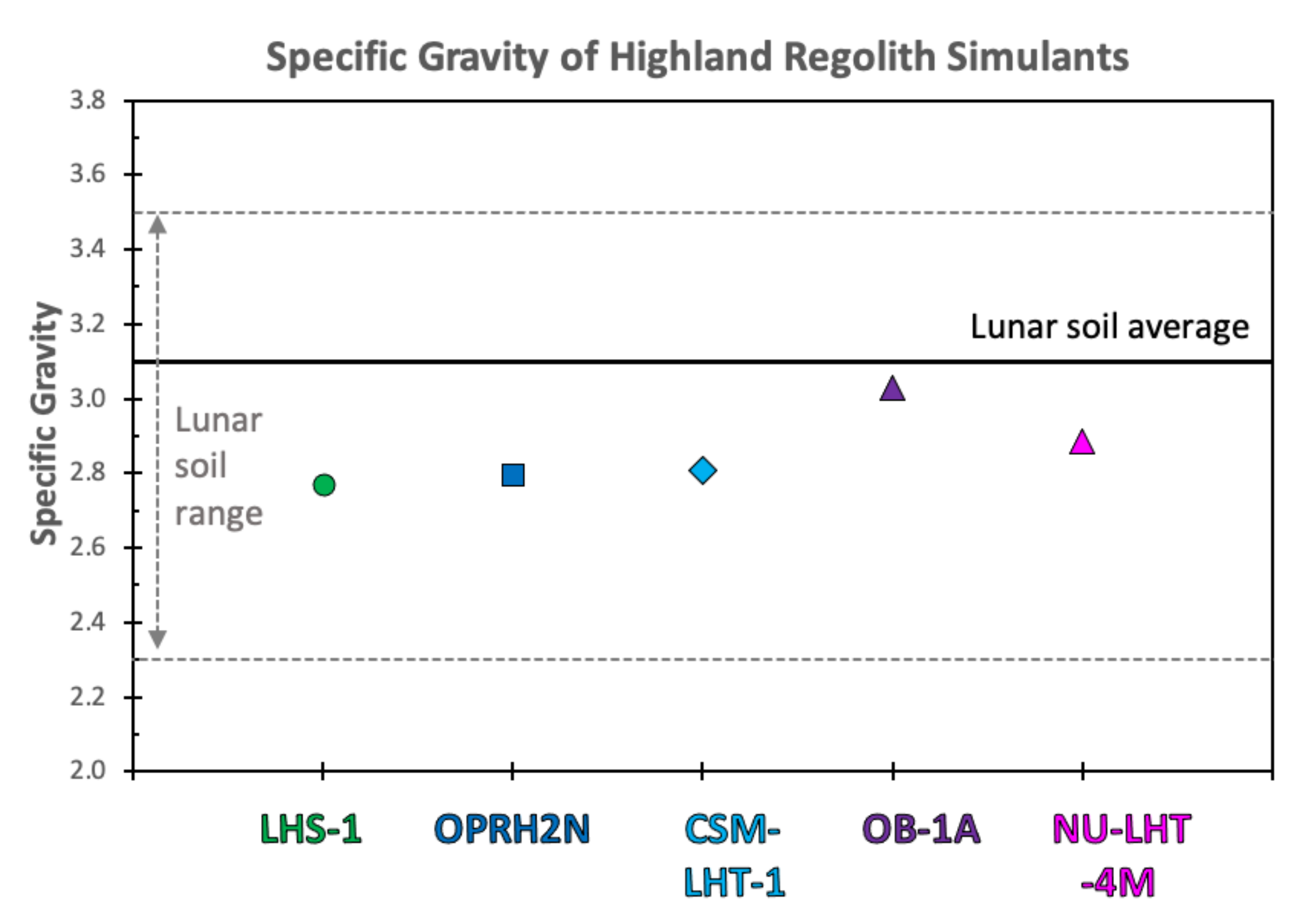
- **Direct Shear Strength measurements**
  - Friction angles within range measured for lunar soils
  - Cohesion exceeds that measured for lunar soils

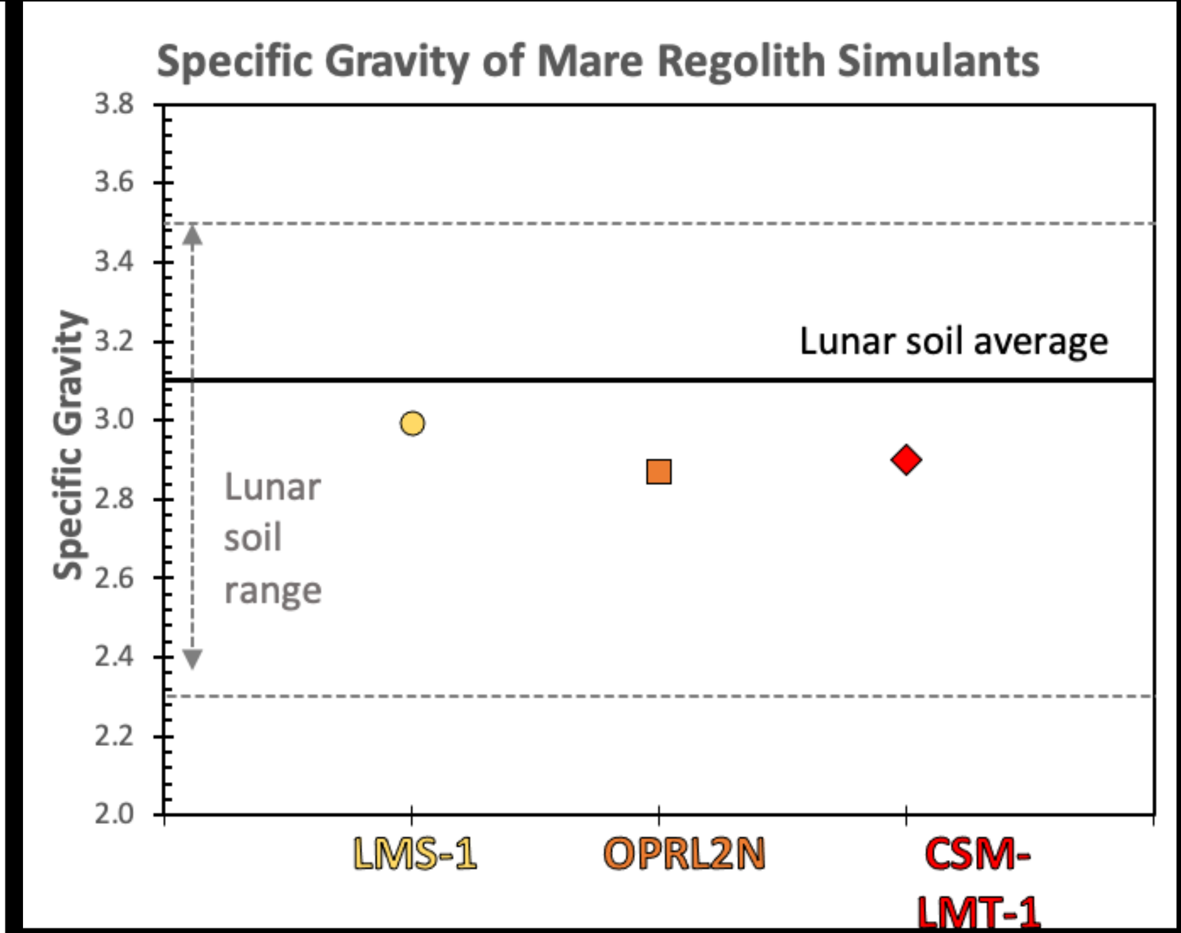




Lunar Simulants – Specific Gravity (2022)

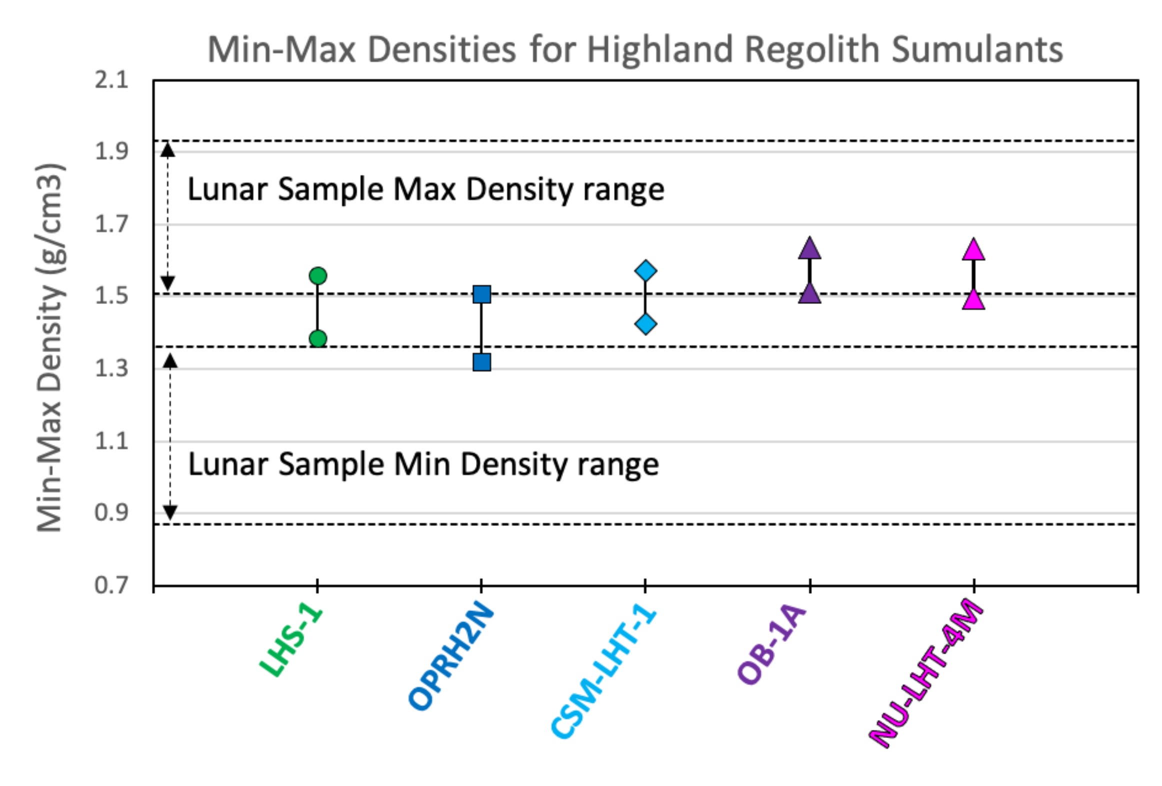
- **Specific Gravity**
  - All simulants have specific gravity values within the range observed for lunar soils

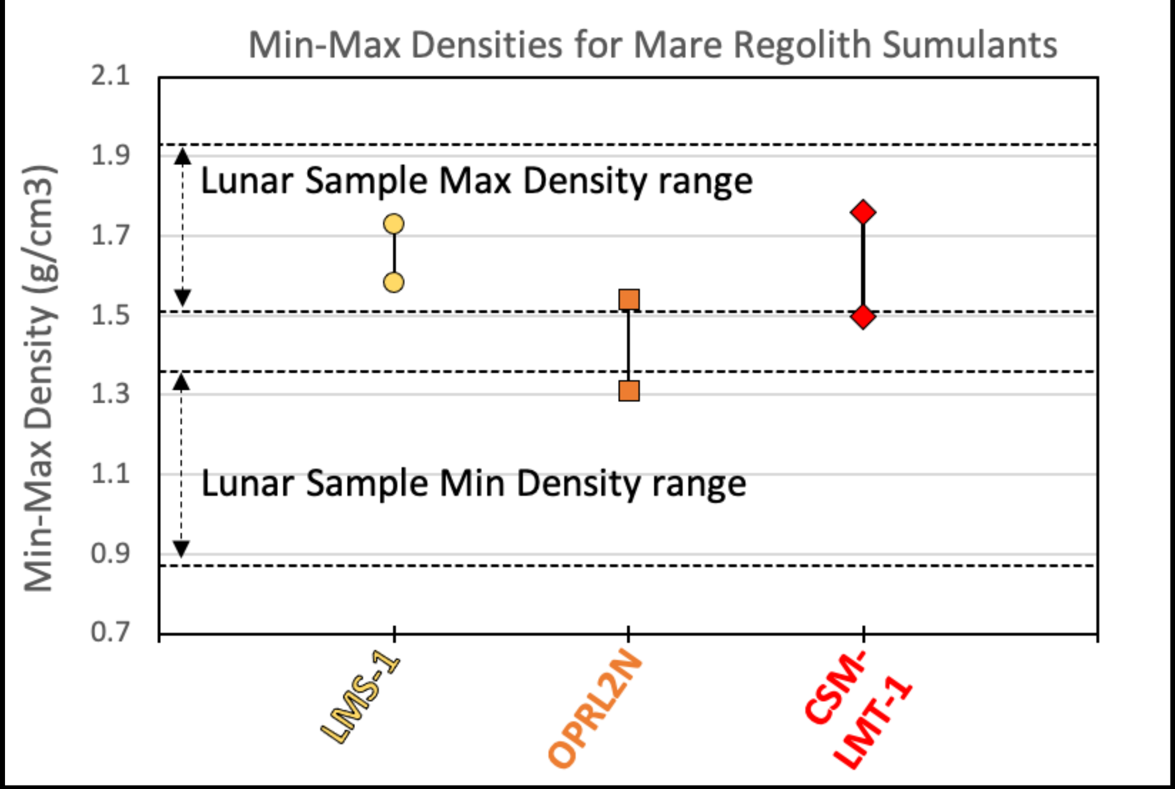




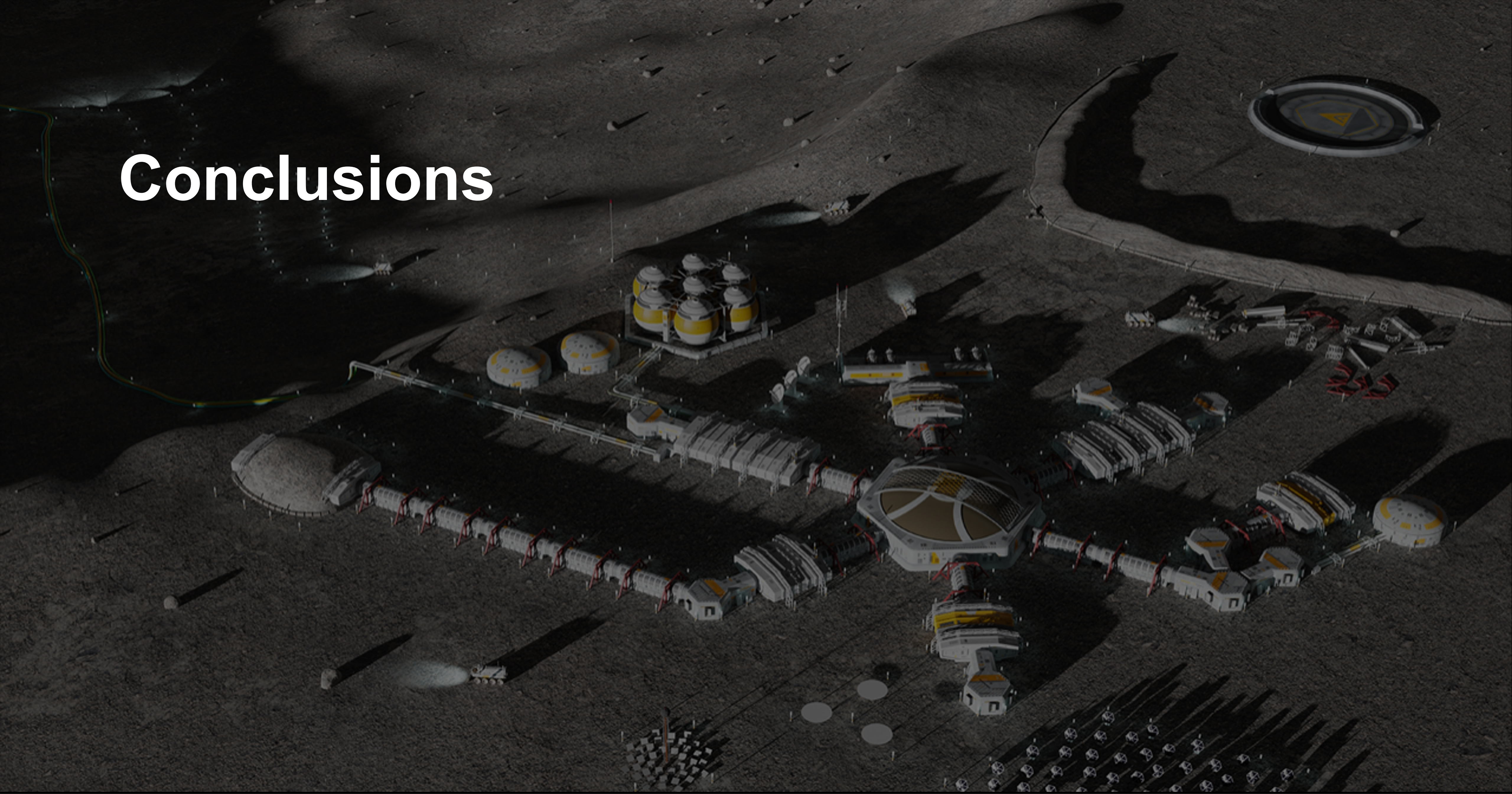
Lunar Simulants – Min & Max Density (2022)

- **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



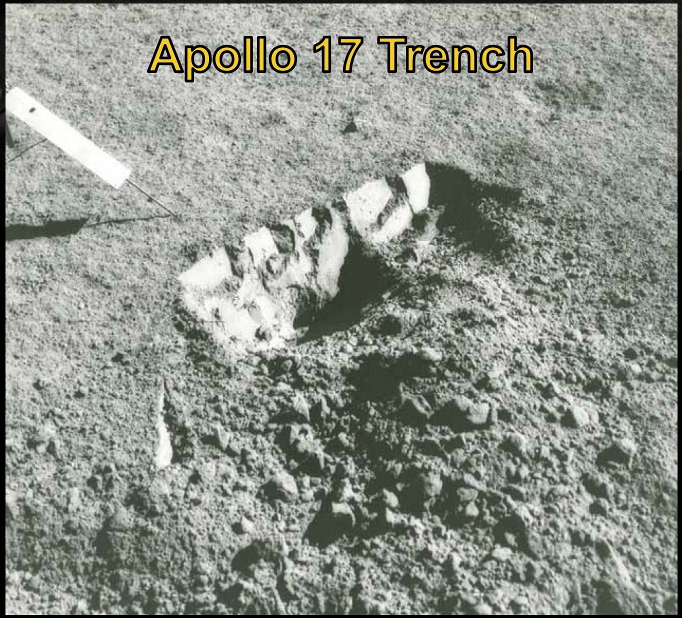


Conclusions



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
      - Petrologic modeling suggests large differences in viscosity of the liquid produced by melting
      - 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



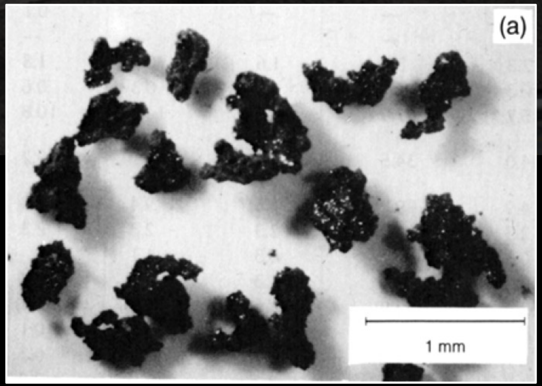
(Fig. 7 in Carrier 2005)

- **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
    - We attempted to compare our data to only earth-based measurements on lunar regolith

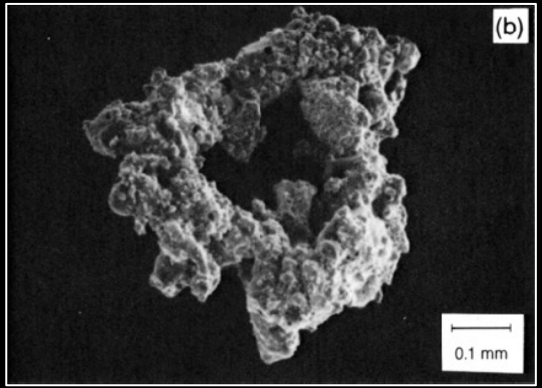
LSII | LSWG Considerations

- **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

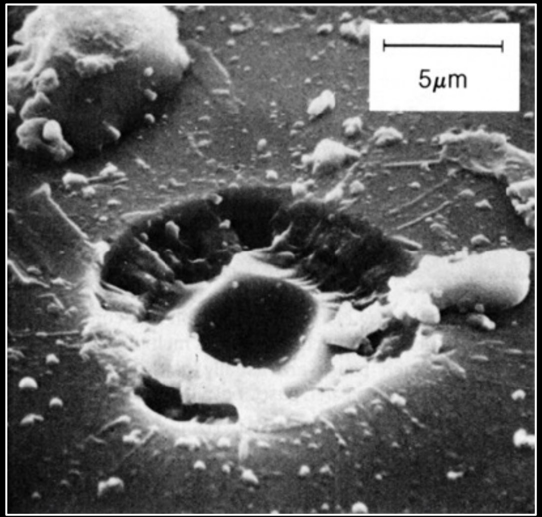
- **For advanced (high TRL) testing, it may be wise to compare results using a simulant with and without pseudo-agglutinate simulant, and potentially even a lunar soil (in the lab or on the lunar surface).**



Apollo 11 agglutinates separates (NASA Photo S69-54827; Fig. 7.2a of McKay et al., 1991).



Close-up of agglutinate particle (NASA Photo S87-38812; Fig. 7.2b of McKay et al., 1991).

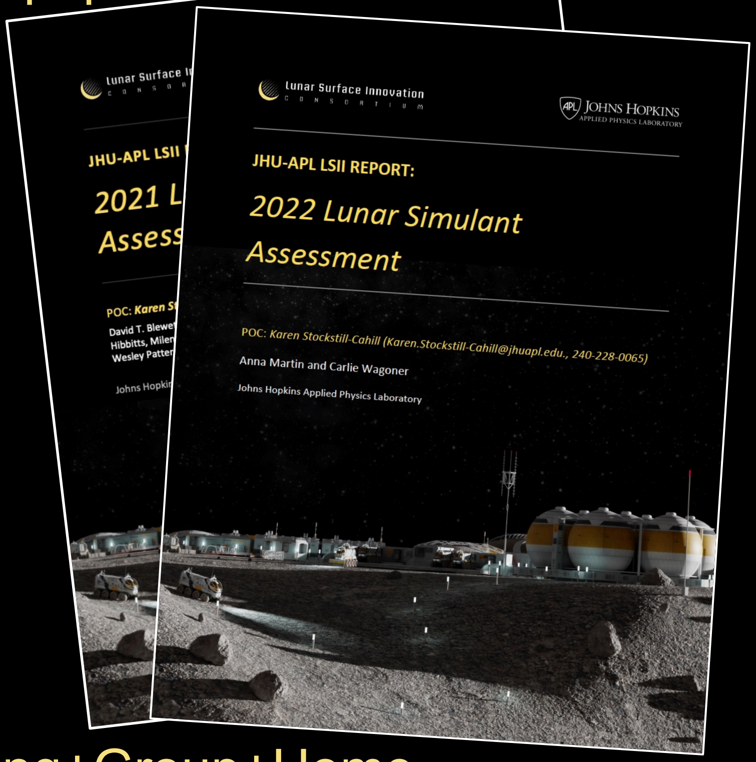


Micrometeoroid impact crater on the surface of a lunar soil particle (Fig. 7.8 of McKay et al., 1991).

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
  - https://lsic.jhuapl.edu/Our-Work/Working-Groups/Lunar-Simulants.php

Please email Karen.Stockstill-Cahill@jhuapl.edu **to be added to new LSWG List Serve**
Format:
henry@somewhere.com Henry Brown



- **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


Lunar Surface Innovation
CONSORTIUM