Advancing Regolith Simulants for High-Temperature Applications K. Edison1 and, C. Dreyer 1,2. 1Colorado School of Mines Space Resources Program, Golden CO, 80401. kedison@mines.edu. 2Colorado School of Mines Department of Mechanical Engineering, Golden CO, 80401.

Introduction: Regolith simulants have historically been developed for geotechnical applications such as rover mobility testing and excavation studies. These simulants are designed to replicate particle size distribution, friction angle, and mechanical behavior. However, as lunar in-situ resource utilization (ISRU) research advances, a growing focus on melting and materials processing has highlighted limitations in existing simulants [6].

Techniques such as casting, sintering, additive construction, and molten regolith electrolysis (MRE) depend on the thermal, chemical, and mineralogical properties of regolith. While some simulants approximate lunar composition, they were not designed for melting behavior, leading to challenges such as foaming, phase separation, and inaccurate crystallization pathways. This work aims to expand regolith simulant capabilities by refining mineralogy, improving chemical fidelity, and developing new approaches tailored for high-temperature processing applications.

Lunar Regolith & Simulant Challenges: Lunar regolith is a complex mixture of rock fragments, mineral grains, impact-produced glass, and agglutinates formed over billions of years. Its composition varies by location: mare regolith is rich in FeO and TiO_2, while highlands regolith is high in Al_2O_3. Glass content is significant due to impact processing, and nanophase metallic iron enhances its microwave absorption properties [4].

Melting experiments on Apollo 14 mare regolith suggest a solidus of ~1,150–1,252°C, while highland regolith may exceed 1,500°C [7]. However, current terrestrial simulants do not always replicate these properties accurately. Many contain hydrous minerals, oxidized Fe (Fe^{3+}), and alkali-rich phases, leading to volatile release, foaming, and altered phase formation. Cooling rate differences also promote devitrification, forming silica polymorphs such as tridymite and cristobalite, which are less prevalent in lunar conditions [5].

A thin section analysis CSM-LHT-1, a highlands regolith simulant, which consists of 70% Greenspar anorthosite from Greenland and 30% Merriam Crater basalt, a high-glass-content scoria [1] showed the presence of hydrous minerals such as micas and clinozoisite. While useful for some applications, its hydrous phases contribute to foaming as reported by [3] and its mineralogy does not fully replicate lunar highland regolith. Targeted refinements are needed to improve simulants for melting applications. Figure 1 shows the resulting micrographs of those hydrous minerals found within the Greenspar.

Figure 1 Handsample and accompanying thin section micrograph of the Greenspar anorthosite showing the presence of hydrouss minerals.

Proposed Solutions: *A New Breed of Simulant*:

1. Improving Basaltic Components

Current simulants often use scoria-based basalt, which has high vesicularity and volcanic glass content, potentially contributing to foaming and phase separation during melting. Replacing it with oceanic basalt (e.g., Hawaiian basalt) could provide a more crystalline structure, higher FeO content, and better melt behavior, aligning more closely with lunar mare regolith.

Benefits:

- Reduced foaming and volatile release.
- Improved crystallization control in cast and sintered products.
- More accurate melt dynamics for lunar basaltic regolith.

Figure 2 compares the average lunar mare composition to the Hawaiian basalt used by PISCES for sintered tiles [2] and the JSC-1A simulant, primarily sourced from Merriam Crater basalt. The fully crystalline Hawaiian basalt, with its higher FeO content, more closely resembles lunar regolith.

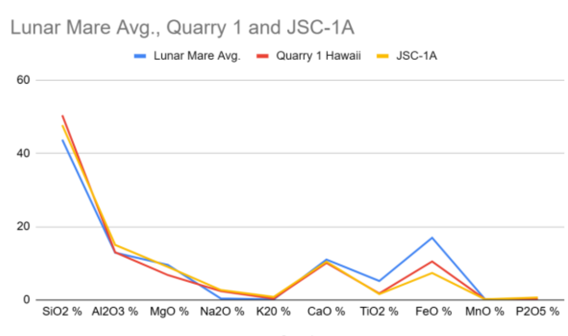

Figure 2, Comparison XRF chart for the lunar mare average, Hawaiian basalt, and JSC-1A.

2. Enhancing Anorthosite Composition

Terrestrial anorthosites contain hydrous phases that release volatiles, creating foaming and defects during melting. Preheating anorthosite to 800°C before processing can effectively dehydrate these minerals, reducing gas evolution and improving melt stability.

Benefits:

- Cleaner melts with reduced porosity.
- Improved casting behavior and sintering consistency.
- More stable highland regolith analogs for high-temperature studies.

3. Introducing a Specialty Synthetic Simulant

Natural simulants inherently vary in composition, oxidation state, and phase behavior, limiting experimental repeatability. Developing a synthetic anorthite-based simulant could offer a controlled benchmark material, ensuring consistent phase transitions and predictable melt behavior.

Benefits:

- Precise melt temperatures that align with lunar conditions.
- Greater consistency in phase transitions and material properties.

Considerations: While a synthetic approach would provide highly accurate data, economic feasibility and production feasibility remains a key factor for future research.

4. Introducing Agglutinate Glass in Simulants

Lunar regolith contains agglutinates, glass-welded particles formed by micrometeoroid impacts. These agglutinates influence melt behavior, viscosity, and phase separation, yet they are largely absent from current simulants due to their geotechnical focus. Creating artificial agglutinates using targeted laser melting or solar sintering can help replicate this key component for melting experiments.

Benefits:

- More realistic melt viscosity and phase interactions.
- Improved accuracy in sintering and casting behaviors.
- Better alignment with expected lunar melt properties.

Considerations: Laser-melting regolith simulant can approximate lunar agglutinates, but refining composition, fraction, and microstructure is needed. Scaling up production for research remains an open challenge. Outward Technologies successfully used powder bed fusion to sinter simulant grains into agglutinate-like structures [1].

5. Introducing an Iron-Enriched Simulant

Lunar regolith contains nanophase iron (np-Fe^0), formed by space weathering, which influences melt behavior, sintering properties, and conductivity. While true nanophase iron is difficult to replicate, increasing the FeO content in simulants could improve chemical fidelity and better approximate the melt properties of lunar regolith.

Benefits:

- More accurate FeO concentrations for molten regolith studies.
- Improved melt dynamics for casting, sintering, and MRE.
- Potentially closer phase equilibria and viscosity behavior in melts.

Considerations: The choice of iron source is critical—metallic iron shavings or fine iron powder could introduce oxidation risks, while iron-rich minerals (e.g., ilmenite, magnetite) may provide a more stable alternative but deviate from lunar regolith. Further research is needed to assess feasibility.

Conclusion: Future regolith simulant development should prioritize modularity, adaptability, and transparency in material selection. Rather than replacing existing simulants, refinements should expand options for high-temperature applications. The next step is optimizing simulants for targeted ISRU processes while ensuring scalability and accessibility.

References: [1] Blewett, D., Bussey, D., Cahill, J., Clyde, B., Denevi, B., Hibbitts, K., ... & Wagoner, C. M. (2021). 2021 Lunar Simulant Assessment. *JHU-PAL LSII Report*.

[2] Edison, K. P., Jeffery Taylor, G., Andersen, C. B., & Romo, R. F. (2023). The Effects of Mineral Variations on the Basalt Sintering Process and Implications for In-Situ Resource Utilization (ISRU). In *Handbook of Space Resources* (pp. 463-489). Cham: Springer International Publishing.

[3] Edison, K. P., & Cannon, K. (2024). Casting Lunar Regolith into Durable Materials. In *Earth and Space 2024: Engineering for Extreme Environments* (pp. 23-33).

[4] Meek, T.T. 1987. A proposed model for the sintering of a dielectric in a microwave field. Journal of Material Science Letters 6: 638–640.

[5] Schrader, C. M., Rickman, D. L., McLemore, C. A., & Fikes, J. C. (2010). *Lunar regolith simulant user's guide* (No. M-1295).

[6] Taylor, L. A., Pieters, C. M., & Britt, D. (2016). Evaluations of lunar regolith simulants. *Planetary and Space Science*, *126*, 1-7.

[7] Taylor, G. J., Martel, L. M., Lucey, P. G., Gillis-Davis, J. J., Blake, D. F., & Sarrazin, P. (2019). Modal analyses of lunar soils by quantitative X-ray diffraction analysis. *Geochimica et Cosmochimica Acta*, *266*, 17-28.