QUANTITATIVE CHARACTERIZATION OF LUNAR REGOLITH SIMULANTS FOR DIRECT COMPARISON TO APOLLO SOIL SAMPLES. R. Kovtun[1], S. Walker[1] and J. Gruener[2], [1] Astromaterials Research and Exploration Science Division, Jacobs Technology, NASA Johnson Space Center, Houston, TX (rostislav.n.kovtun@nasa.gov), [2] ARES, NASA Johnson Space Center

Introduction: Sustained characterization efforts of lunar regolith simulant properties are not only integral for verification of commercially-produced material designed for a wide array of testing applications but are also necessary in establishing a comprehensive comparison to a lunar reference source. As a resource for the lunar science and engineering communities, the Simulant Development Lab (SDL) within the Astromaterials Research & Exploration Science (ARES) division at the Johnson Space Center (JSC) is actively pursuing closure of existing knowledge gaps in fundamental simulant attributes, including chemistry, mineralogy, particle size distribution, particle geometry, bulk and relative density, magnetic susceptibility, and shear strength (i.e., cohesion and angle of internal friction), as well as producing Figures of Merit for comparison of lunar simulants to Apollo regolith samples.

Background: Lunar regolith simulants have been utilized since the early 1970s following preliminary analysis of samples returned by the inceptive Apollo missions [1]. Due to a paucity of physical lunar soil samples, the creation of simulant materials was integral for sustaining a widespread instrument testing and data collection campaign that has only ramped up in preparation for the upcoming Artemis missions to the lunar surface. While demand for lunar regolith analogs has increased, characterization efforts have not kept pace with the development and manufacturing of simulant materials.

As a result of extensive experimentation and analysis, there is a trove of compositional (i.e., chemistry, mineralogy) and physical (i.e., PSD, density, specific gravity, etc.) data on returned Apollo soil samples [2]. Although peripheral information regarding fundamental properties of available lunar simulants exists, much of the data remains unverified, lacks organization, and/or is missing entirely. Thus, characterization efforts are necessary to ascertain the primary property attributes of lunar simulant material, both as a means to fill in existing knowledge gaps as well as provide a template for verification and validation of produced simulant material. Furthermore, due to a demand for an increasing fidelity in lunar analog material to match increasing levels of hardware flight readiness and general technological progression, there must be a means for comparing a particular lunar simulant to an actual lunar regolith reference material.

Figures of Merit. The Figures of Merit project was initially introduced as a method for comparing lunar and terrestrial materials based on a quantitative interpretation of the similarities in primary properties between samples [3]. The calculated Figure of Merit is derived from the normalized difference between two primary property vectors (one represents the regolith sample while the other represents the corresponding simulant attribute) subtracted from unity (Figure 1). Thus, the final Figure of Merit product should lie between 0 and 1, where 1 denotes a perfect match between materials and 0 indicates no match.

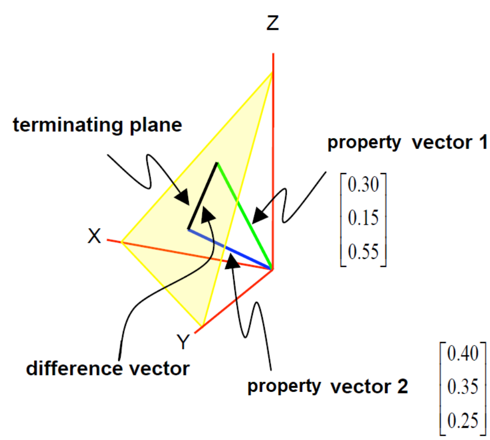

Figure 1. Schematic of the L1-normed property vector space where x+y+z = 1. Values are shown as an example of the constiuents vector inputs [modified from 3].

Due to the robustness of primary property attributes for granular materials, several equations were developed to incorporate the variability in the compositional parameters of the lunar simulants and their regolith reference points [4]. Initially, four characteristics were compared between samples: composition, particle size distribution, particle shape, and density.

Following some progressive iterations [5], the Figures of Merit project has evolved to incorporate additional fundamental properties, including magnetic susceptibility and shear strength (i.e., cohesion and angle of internal friction) parameter values. Furthermore, several of the incipient primary properties utilized in Figure of Merit calculations have been altered to better reflect the current engineering and technology needs. Changes include the differentiation of the compositional parameter into individual mineralogy and chemistry categories, focusing the particle shape quantification on sphericity and aspect ratio measurements, and expanding the density characterization to include both bulk and relative values.

Methods: The Simulant Development Lab (SDL) has undertaken an expansive effort to characterize the primary properties of lunar simulant with the intent of leveraging the acquired data to perform quantitative analysis as a means to produce comparative Figures of Merit for commercial and NASA-affiliated simulant materials. The SDL has aggregated available simulant, as well as pertinent Apollo samples, data from literary sources, manufacturer datasheets, and independent labs both in academia and industry. Additionally, the SDL has performed novel simulant characterization work on-site at JSC.

Compositional property data. Modal mineralogy for Apollo samples was derived from X-ray diffraction (XRD) analysis completed by Taylor et al. 2019 [6]. Simulant modal mineralogy data was aggregated from literary sources, including the 2021 Lunar Simulant Assessment prepared by the Johns Hopkins Applied Physics Laboratory [7]. Additionally, preliminary powder XRD analysis with Rietveld refinement was completed on a variety of simulants at the NASA ARES XRD Research Lab. Bulk oxide chemistry data was similarly aggregated from various literary sources, including the 2021 APL assessment report [7]. The majority of the measurements were determined via X-ray fluorescence (XRF) analysis.

Physical property data. Particle size distribution (PSD) analysis was performed by a MicroTrac BlueWave laser particle size analyzer at the NASA ARES M3EGA lab. Additional PSD data and all 3D particle geometry data were derived via laser diffraction and dynamic image analysis using a MicroTrac SYNC at the SDL and an identical instrument at the Colorado Schools of Mines, independently [5]. Density and shear strength values were taken from literary sources [8]. Magnetic susceptibility measurements have yet to be completed, so no verifiable data currently exists.

Simulant Figure of Merit calculations are performed at the SDL via a MATLAB executable script. While several incipient algorithms are remnant, the majority of the functions are derived from Metzger et al. 2019 [9].

Anticipated products: The SDL will produce a data repository housing the calculated Figures of Merit and accompanying material property input values for individual simulant, as well as pertinent Apollo sample data. Additionally, Figure of Merit report cards incorporating weighted use case scores and visual pictograms representing the suitability of a particular simulant for a generalized task (Figure 2). These use cases scores are derived from five general groups of use cases: geotechnical, particle bonding, particle-surface interactions, chemical processing, and human health. Each use case group is given an overall use case score per simulant based on weighted values of pertinent property parameters.

Figure 2. Example of a simulant report card with use cases and representative pictograms.

Future Work: Characterization efforts for lunar simulants is ongoing. Additional compositional measurements, including XRD and XRF analysis, are required. Furthermore, physical parameters such as relative density, shear strength, and magnetic susceptibility of simulants still need to be measured. There is an ongoing geotechnical assessment utilizing direct shear testing at JHU-APL, with further independent analysis slated to begin in 2023. Also in the upcoming year, magnetic susceptibility measurements will be performed within the SDL via a Bartington MS2/MS3 system.

References: [1] Taylor L. A. et al. (2016) *Planetary & Space Sci., 126,* 1-7. [2] Heiken G.H. et al. (1991) *Lunar Sourcebook.* [3] Rickman D. (2007) *ISO/TC20/SC14*, May 20-25. [4] MSFC-RQMT-3503 (2007). [5] Deitrick S.R. and Cannon K.M. (2021) *Space Resources Roundtable.* [6] Taylor G. J. et al. (2019) *Geochimica et Cosmochimica Acta, 266,* 17-28. [7] Stockstill-Cahill K. et al. (2021) *JHU-APL LSII Report*. [8] He C. (2010) *PhD dissertation,* Case Western Reserve Univ. [9] Metzger et al. (2019) *Icarus*, *321,* 632-346