3D PARTICLE GEOMETRY CHARACTERIZATION OF APOLLO REGOLITH SAMPLES VIA LASER DIFFRACTION AND DYNAMIC IMAGE ANALYSIS.

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Introduction: Establishing a fundamental understanding of regolith mechanics hinges on the characterization of the foundational physical parameters that dictate granular particle interactions both on micro- and macro-scales. Specifically, particle size distribution, particle geometry and grain density govern the geotechnical properties, including compressibility, shear strength, hydraulic conductivity (i.e., permeability), void ratio (i.e., porosity), and thermal conductivity of the lunar regolith. The absence of terrestrial geologic processes on the lunar surface, a lack of water, clay minerals, and organic material in lunar soils, and the narrow compositional range in terms of mineral diversity of the regolith produces a unique problem when attempting to project terrestrial soil mechanics concepts to the lunar surface. Additionally, the occurrence of agglutinates, exclusive to the lunar surface, further disassociates the physical behavior (e.g., particle crushability, flowability, etc.) of regolith from that observed in terrestrial soils.

Background: Defining the geotechnical properties of lunar regolith is integral in the design and implementation of testing protocols as NASA ramps up its lunar exploration effort with the upcoming Artemis mission campaign. Due to the paucity of physical Apollo samples available for instrument and tool testing at scale, there is a need within the space science and engineering communities for lunar regolith simulants at variable levels of fidelity. The Simulant Development Lab (SDL), a part of the ARES division at the NASA Johnson Space Center (JSC), is actively conducting a characterization effort of both commercial and NASA-derived simulants in order to produce Figures of Merit, which quantitatively compare the physical (i.e., PSD, particle geometry, bulk and relative densities, and shear strength) and compositional (i.e., mineralogy and chemistry) properties of simulant material to a lunar reference.

While most of the data attained from the ongoing simulant characterization effort can be directly correlated to discrete data points derived from a combination of Apollo-era and contemporary studies of lunar samples, there is an existing knowledge gap in the existing particle geometry specifications. Fundamentally, there is a lack of three-dimensional particle geometry data for lunar samples due to the technological constraints that existed during the initial characterization of lunar particle shapes. As Chapter 9 of the Lunar Sourcebook outlines, all the particle shape parameters for Apollo return samples, including elongation, aspect ratio, roundness, volume coefficient and specific surface area, were derived from observational measurements limited to a 2-D space. Additionally, the values are derived from an extremely limited sample size, with some shape parameters determined from as few as 30 individual particles [1] while other measurements are taken from unpublished sources [2]. The outstanding concern with these poorly constrained datasets is that the values are incorporated in contemporary NASA guidelines and requirements documentation (e.g., DSNE).

By leveraging recently developed imaging and laser diffraction technologies, we propose to conduct a thorough investigation of 2D and 3D particle geometry parameters of lunar samples of varying maturity levels and composition. Compared to the observational measurements produced by the Apollo-era particle shape studies, contemporary instrumentation allows for expansive data acquisition with one measurement encompassing a wide array of geometry and size properties of several hundred thousand of particles. Acquiring 2D and 3D lunar regolith particle geometry data over an extensive sample size would establish a reference point for direct comparison to simulant shape data feeding into the ongoing Figures of Merit project, as well as create a database of particle shape values for Apollo samples that can be referenced in future iterations of pertinent NASA guidelines and documents.

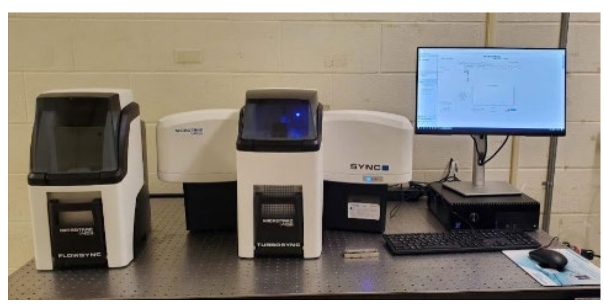

Figure 1. MicroTrac SYNC particle and shape analyzer at the Simulant Development Lab (JSC)

Analytical Method: The particle size and geometry analyses will be done using the Microtrac SYNC particle analyzer located in the Simulant

Development Lab (SDL) at NASA Johnson Space Center (Fig. 1). The SYNC integrates tri-laser diffraction (LD) technology with dynamic image analysis (DIA) to characterize particles using a unique measurement system. It provides particle size distribution (PSD) information using LD technology for particles ranging from 0.01 microns to 4000 microns as well as morphological parameters for each particle through DIA. More than 30 size and shape parameters are collected for each individual particle (Table 2). For each measurement, 0.3 g of a sample will be added to the SYNC which will result in the analysis of > 100,000 particles through LD and DIA, outputting the parameters shown in Table 1 as well as the data and graphs shown in Figure 2. The instrument was calibrated by Microtrac before delivery as well as during installation. Before each new sample is analyzed, the instrument is rinsed, and a set zero background is collected to cancel out any background noise which is then followed by three repeat measurements of the same sample.

Size Parameters	Shape/Form Parameters	Surface Roughness Parameters	Other Parameters
Diameter	Sphericity	Convexity	Transparency
Area	Circularity	Solidity	Curvature
Volume	Roundness	Concavity	
Perimeter	Extent		
Surface Area	Ellipse Ratio		
Convex Hull Surface Area	Aspect Ratio		
Cylinder Diameter	Ellipticity		
Cylinder Length	Angularity		
Fiber Length	Rectangularity		
Fiber Width	Compactness		

Table 1. Output parameters for MicroTrac SYNC

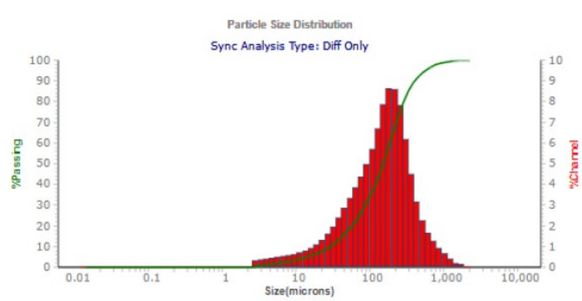

Figure 2: Particle size distribution example produced by MicroTrac SYNC instrument

Id	21933	
Img Id	1073	
Da	167.113	µm
Dp	182.381	µm
FLength	217.442	µm
FWidth	148.672	µm
ELength	200.509	µm
EWidth	142.598	µm
Volume	2443608.26	µm≥
Area	21933.697	µm≤
Surface Area	87734.789	µm≤
Perimeter	572.967	µm
CHull Area	22579.284	µm≤
CHull Surface Area	90317.138	µm≤
CHull Perimeter	564.062	µm
Sphericity	0.916	
L/W Ratio	1.463	
W/L Aspect Ratio	0.684	
Ellipse Ratio	0.711	
Ellipticity	1.406	
Compactness	0.769	
Roundness	0.591	
Extent	0.678	
Circularity	0.84	
Solidity	0.971	
Concavity	0.029	
Convexity	0.984	
Transparency	0.115	
Curvature	0	

Figure 3: Individual grains of NU-LHT-2M simulant by Dynamic Image Analysis (top) and accompanying measurement outputs (bottom). Modified from [3]

Future Work: This project will produce a data repository complete with 3D particle geometry and particle size distribution data for approximately 12 individual lunar regolith samples. Additionally, lunar simulant shape and size data will be incorporated into the database to facilitate an off-hand comparison between simulants and Apollo samples.

References: [1] Heywood H. (1971), *Proc. Lunar Sci. Conf. 6th*, 1625-1651. [2] Mahmood et al. (1974b), *Unpublished* as found in the Lunar Sourcebook. [3] Deitrick S. and Cannon K. (2022) *53rd Lunar and Planetary Science Conference*