CHARACTERIZING DETAILED GRAIN SHAPE AND SIZE DISTRIBUTION PROPERTIES OF LUNAR REGOLITH. S. R. Deitrick,[1,2] S. C. Coutts,[1] and K. M. Cannon,[1] [1]Space Resources Program, Colorado School of Mines, Golden, CO, [2]Astromaterials Research and Exploration Science Division, Jacobs Technology, NASA Johnson Space Center, Houston, TX, sarah.r.deitrick@nasa.gov.

Introduction: As the nation prepares to return to the Moon, there is an increasing need for testing tools, instruments, and equipment in simulated environments on Earth to ensure successful operations during lunar missions. Regolith will affect all aspects of future lunar missions, from plume interactions during landing to space suit and tool design [1]. Because of this, it is important to understand the grain shape and size properties of lunar regolith and how those influence regolith behavior in order to prepare for these missions. While particle size analyses have been performed on most Apollo soils using simple sieving, shape has only been crudely addressed [2]. This work analyzes 4 lunar regolith samples to provide a better understanding of these size and shape parameters and will provide a more accurate baseline of data to create high-fidelity lunar regolith simulants.

Methods: New technologies exist today that are capable of measuring size and shape simultaneously for hundreds of thousands of particles in a single measurement. We conducted a rigorous analysis of the particle size distribution (PSD) as well as the size-dependent 2D and 3D shape parameters of lunar regolith samples of different compositions and maturity levels. This analysis was done using a Microtrac SYNC which provides a unique combination of tri-laser diffraction and Dynamic Image Analysis (DIA).

Sample Selection. Four regolith samples were selected for analysis based on maturity level and lunar terrain type:

- 10084 – Mature high-Ti mare regolith
- 15601 – Immature low-Ti mare regolith
- 64501 – Mature highland regolith
- 67461 – Immature highland regolith

Sample Analysis. After receiving the samples, each sample was imaged with an optical microscope (Figure 1). To obtain 2D and 3D particle size and shape, 0.1 g of each sample was then added to the SYNC for analysis, which outputs more than 30 size and shape parameters for each individual grain as well as the complete size distribution from 0.01-2000 µm by blending laser diffraction and DIA together. For the 0.1 g sample masses requested, ~100,000 grains per sample were captured by DIA.

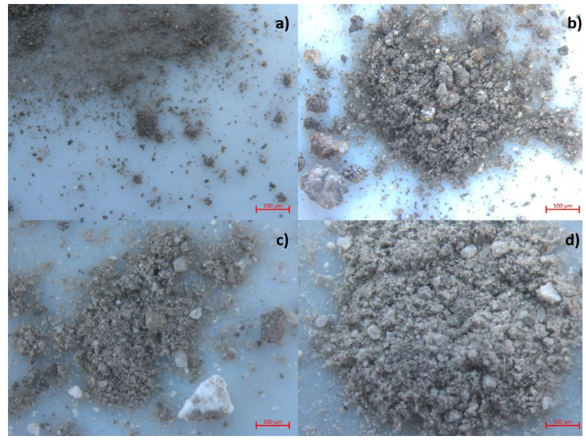

Figure 1. Microscopic images of regolith samples 10084 (a), 15601 (b), 64501 (c), and 67461 (d). Red scale bar is 100 µm.

Following the sample analysis, a machine learning method was used to assign individual particles to distinct clusters. We chose to investigate this method under the premise that accurate particle classification would allow for improved estimates of geotechnical properties. Specifically, if particles could be classified by shape, then the proportion of differently shaped particles could be determined and mapped to the resulting geotechnical properties.

The clustering method used a feature extraction step followed by a clustering step. In computer vision, a feature represents a specific structure found within an image (sharp edge, hole, etc.). In the feature extraction step, Google's Inception V3 network was used to extract features from a subset of the particle dataset (10,000 images). The Inception V3 network is a widely used convolutional neural network trained on the ImageNet Dataset (1,331,167 images). In the clustering step, the k-means algorithm was used to group the particles into 4 clusters, based on their extracted features.

Results: From the PSD analysis (Figure 2), the average particle size of 10084 is ~24.5 µm which is much smaller than the average particle size of the Apollo sample collection (~72 µm) [3], while the average particle size of samples 15601, 64501, and 67461 are larger than the Apollo sample average at ~106 µm, ~103 µm, and ~118.5 µm respectively.

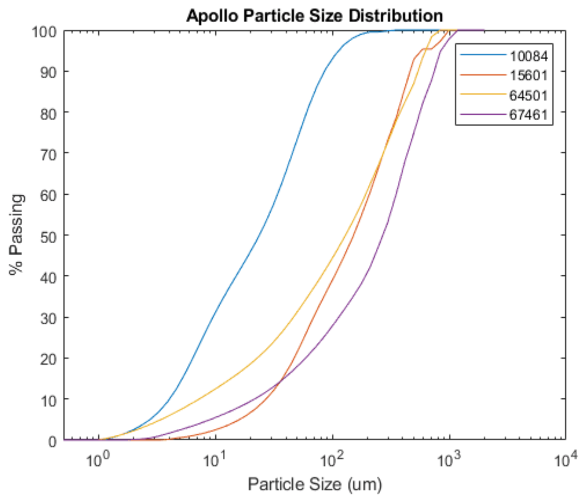

Figure 2. PSD graph for each of the four lunar regolith samples.

The size and shape measurements for the samples output ~30 parameters, four of which were focused on for this study: sphericity, aspect ratio, roundness, and concavity. However, after analyzing the samples it was found that only sphericity and aspect ratio showed differences between the samples. These two parameters are measured on a scale from 0 to 1, with 1 being a perfect sphere with equal dimensions. The results show that the sphericity values are slightly higher for the mature samples 10084 and 64501 (~0.96) than they are for samples 15601 and 67461 (~0.95). The aspect ratio values are slightly lower for samples 64501 (~0.7) and 67461 (~0.74) than they are for samples 10084 (~0.76) and 15601 (~0.8).

From the particle clustering, the particles were separated relatively evenly between the 4 clusters (2019 particles, 3222 particles, 1885 particles, and 2234 particles in clusters 1-4 respectively). Although there were clear anomalies, each cluster appeared to represent a distinguished particle shape. Cluster 1 contained a high portion of particles with highly transparent internal areas. Cluster 2 contained mostly rounded spherical particles, cluster 3 contained thin, elongated particles, and cluster 4 contained angular particles that are slightly wider than those in cluster 3 (Figure 3).

Discussion: Mature regoliths are those that have been exposed to micrometeorite and solar wind bombardment for longer periods of time, breaking up particles and causing them to become more rounded [4]. Therefore, the smaller particle sizes and higher sphericity values for samples 10084 and 64501 are expected due to their higher maturity level compared to 15601 and 67461. However, the aspect ratio values are not dependent on maturity and are instead dependent on terrain type. The lower aspect ratio values for the highland samples are potentially due to the higher plagioclase content, which occurs in elongated particles and does not break down as easily as the pyroxenes or olivines that are more prevalent in the mare.

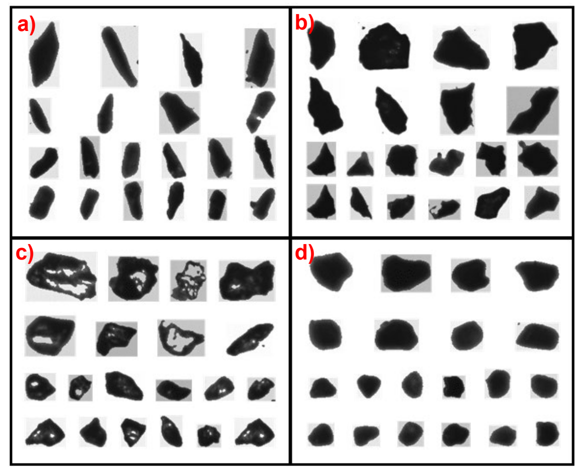

Figure 3. Random sample of 20 particles from each cluster. (a) thin, elongated particles, (b) angular particles, (c) particles with highly transparent internal areas, (d) rounded particles.

Conclusion and Future Work: The results of this work provide a baseline of high-quality data that will contribute to the creation of high-fidelity lunar simulants and will greatly benefit NASA and commercial efforts of establishing a human presence on the Moon. Future work includes training an unsupervised image classification model with a larger dataset of ~10^5 particle images, optimizing the number of clusters using standardized metrics (e.g., elbow method, silhouette method), validating the classification model using detailed shape properties to run statistical tests (e.g., sphericity, aspect ratio, roundness, and concavity), and classifying different samples with the model to investigate the relationship between geological conditions and particle type.

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References: [1] Taylor, L. A. et al. (2005) *AIAA* #2510. [2] Katagiri et al. (2015) *ASCE.* [3] Carrier III, W. D. (2005) *Lunar Geotech Institute Tech Report*. [4] McKay, D. S. et al. (1991) *The Lunar Sourcebook, Chapter 7.*