Asteroid Regolith Model and Figure of Merit for Asteroid Simulants. P. T. Metzger[1], D. T. Britt[2], K. Cannon[2], C. Schultz[2], K. D. Grossman[3], J. D. Mantovani[3], and R. P. Mueller[3]. [1] Florida Space Institute, University of Central Florida, Orlando, Florida, USA, Philip.T.Metzger@ucf.edu, [2] Department of Physics, University of Central Florida, Orlando, Florida, USA. [3] Granular Mechanics and Regolith Operations, Engineering and Technology Directorate, NASA Kennedy Space Center

Introduction: Asteroid regolith simulants are needed for a wide range of technology tests and mission preparation activities, including asteroid water extraction, anchoring tests, and thruster plume/dust interactions. Developing simlants is made difficult by the fact that very little regolith material has been returned from asteroids and other data sets are limited, so the particle size distribution of asteroid regolith is not well-constrained. Mineralogy and other properties are well-constrained by the analysis of meteorites.

Regolith Particle Size Distribution Model: Because we do not have an adequate sample of regolith returned from asteroids, we must develop a model to take its place. We reviewed the primary data sources: (1) regolith particles returned from asteroid Itokawa by the Hayabusa mission; (2) images of boulders photographed on asteroids; (3) telescopic infrared measurements of asteroid surfaces heating and cooling as they rotate in the sunlight; (4) modeling of particulate clouds observed evolving in the solar wind after ejection from asteroid-asteroid impacts; and (5) the "fossilized" regolith contained in regolith breccia meteorites.

Combining Haybusa returned samples and imagery, we found that the surface regolith fines fits a power law with cumulative index -2.5, which is coarser that regolith in collisional equilibrium (-3.5 [1]). For the thermal infrared data, the analysis of Gundlach and Blum [2] shows that larger asteroids generally have finer regolith, but the quantitative predictions of particle size do not match Itokawa data when whole-asteroid averages of the particle sizes are performed. Therefore, we do not believe we can utilize the IR data at this time.

Table 1. Disrupted asteroids. From [3] and references therein.

Disrupted Asteroid	Diameter (km)	D_{min} (mm)	D_{max} (mm)	q
P/2010 A2	0.2 – 0.3	0.6	40	-3.45
P/2012 F5	~ 1 – 2.9	0.04	560	-3.7
596 Scheila	113	0.0016	100	-3.5
Emilkowalski	~ 10	--	--	-3.1

For disrupted asteroids (see Table 1), we found that maximum and minimum particle sizes vary with the parent asteroid but may be artifacts of the ejecta dynamics or measurement sensitivities. However, the cumulative power law index q is consistently ~ -3.5, with the slightly coarser Emilkowalski ejecta distribution explained by its greater age so fines have been winnowed away.

For the texture in regolith breccia meteorites we find that fitting a power law to the data predicts a cumulative power index of about -1, much coarser than all other data reviewed above. This suggests the regolith on the parent body where it was excavated was much less mature than the regolith ejected in the recent asteroid disruptions. Overall, we conclude the model for asteroid regolith should be a power law. Its maximum and minimum particle sizes should be determined by the simulant users to represent whatever size asteroid they wish to replicate, and the power law cumulative index should be -2.5 to simulate the weathered surface regolith or -3.5 to simulate subsurface, bulk regolith.

Figure of Merit for Asteroid Simulants: NASA prescribed use of a "Figure of Merit" (FoM) system to grade lunar regolith simulants [4]. That prior system consisted of four FoMs per simulant: (1) mineralogical composition, (2) bulk density; (3) particle size distribution; and (4) particle shape distribution. Each FoM was calculated by comparison to a reference material, a specific Apollo soil sample representing either highlands or maria regolith as appropriate. To apply this system to asteroid simulants, we developed a total of 8 FoMs based on the different predicted uses of the simulants: (1) mineralogical composition, (2) elemental composition, (3) average grain density, (4) cobble bulk density, (5) cobble mechanical strength, (6) magnetic susceptibility, (7) particle size distribution, and (8) volatile release patterns. We followed NASA developing the system as a set of norms in L1 (Lebesgue) algebra. For particle sizing, the FoM is calculated by comparison to the regolith model presented above. For the other properties, the FoM is calculated by comparison to a selected meteorite.

We tested the new FoM system by calculating values for the newly developed CI asteroid simulant, DSI/UCF-CI-1. The selected reference meteorite for CI is the Orgueil meteorite.

The simulant was found to have a cumulative power law (best fit) of -3.64. The particle size FoM was found by integrating on a logarithmic particle size scale the absolute value of the difference between the simulants' and the models' curves shown in Fig. 1. The logarthmic integral is used to give equal weight to fines as to course particles, since all parts of the spectrum are vital in soil mechanics This integral is divided by $Log_{10}(3.5)$ scaling factor then subtracted from 1. The FoM is thu 0.89 (a scale of 0 to 1) for bulk regolith and 0.57 for surface regolith.

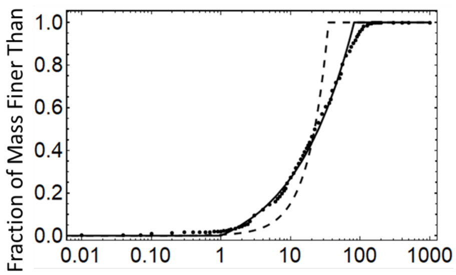

Figure 1. Mass-finer-than curves for simulant (dots), reference model for bulk with -3.5 power index (solid line), and reference model for surface with -2.5 power index (dashed line). Reference models have maximum and minimum sizes chosen to optimize the FoM since inadequate asteroid data exist to constrain these parameters and they are chosen to not reduce the FoM scores.

The cumulative volatile release patterns for Orgueil and the CI simulant are shown in Fig. 2. The FoM for volatile release is defined as the area between the curves (over the range ambient to 1000 °C) normalized by the total area under the black (reference) curve. It is found to be 0.53. Water extracted from asteroid simulant is shown in Fig. 3.

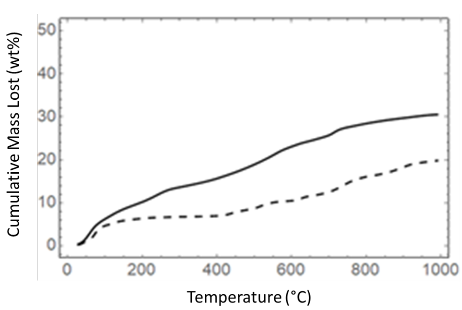

Figure 2. Cumulative mass loss (wt%) for Orgueil meteorite (solid black, data from King et al. [6]) and CI simulant (dashed black).

The elemental and mineralogical FoMs are calculated the same way NASA defined the lunar soil mineralogical FoM. The % mass of each element or mineral is written in rows with the value for the simulant and the value for reference material in adjacent columns. The lesser value in each row is chosen, and these are summed. If the simulant and reference material were identical, the sum would be 1. If they had no compositional overlap, the sum would be 0.

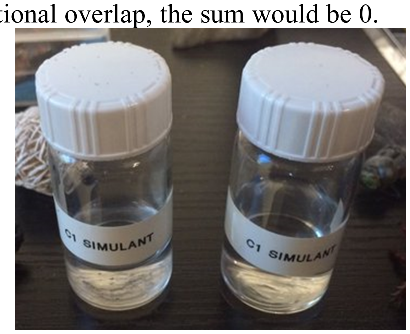

Figure 3. Water thermally extracted from asteroid regolith by Zacny, et al. [5].

The average grain density and cobble bulk density FoMs are both calculated by finding the difference between the simulant and reference material values, dividing this by the reference material value, then dividing by a weight factor (0.5) and subtracting from 1. The cobble strength and magnetic susceptibility FoMs are similar but are on a logarithmic scale since these values can vary over orders of magnitude. The difference in the log of the two values is calculated then divided by the weight factor of $\log_{10}(5)$ and this is subtracted from 1. All the FoMs measured for the simulant are reported in Table 2. These compare favorably with the FoM values of lunar simulants that are typically in the range of 0.2 to 0.4 [4].

Table 2. CI Simulant FoMs.

Figure of Merit	Calculated FoM
Mineralogical	0.83
Elemental	0.94
Mineral Grain Density	0.75
Cobble Bulk Density	0.72
Magnetic Susceptibility	0.96
Cobble Strength	0.77
Volatile Release	0.53
Particle Sizing:	
Bulk Regolith	0.89
Surface Regolith	0.57

References: [1] Dohnanyi J. S. *JGR*, 74, 2531. [2] Gundlach B., and Blum J., *Icarus* 223.1, 479. [3] Metzger P. T., submitted to *Icarus*. [4] Schrader, C. M., et al.. NASA TM 2010–216446. [5] Zacny K., et al., AIAA 2016-5279. [6] King A. J., *Geochim. et Cosmochim. Acta* 165, 148

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