MEASURING THE FIDELITY OF ASTEROID REGOLITH SIMULANTS.

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Introduction: The lunar research and technology community has had problems with lunar soil simulants. Ad hoc simulants have flourished with low pedigree [1,2,3]. Simulants that fail to replicate their documented properties have been manufactured and delivered [4]. Simulants have been too-often misused; for example, simulants designed to replicate only the Moon's geotechnical properties have been used in tests of chemical extraction processes [1,2]. NASA awarded Deep Space Industries and the University of Central Florida a contract to develop high fidelity asteroid regolith simulants [5] and required the team to implement a NASA-developed process for mitigating and preventing these types of problems. The process includes a Figure of Merit (FoM) system that compares each simulant to selected extraterrestrial samples [6]. The FoMs NASA developed for lunar soil were four: modal mineralogy, particle size distribution, density (including maximum and minimum bulk densities and average specific gravity of the grains), and particle shapes distribution. NASA judged that other properties such as internal friction and cohesion derive from these four, so grading a lunar simulant on just these is adequate. Each FoM is recalculated when comparing to a difference reference sample, so a simulant may have a high mineralogy FoM compared to a lunar mare sample but a low mineralogy FoM compared to a lunar highlands sample. The NASA system next considers all the FoMs and ranks simulants in a "Fit to Use" table, telling which simulants are the best choices for which types of tests, such as mechanical drilling in highlands, or chemical extraction from mare.

This paper reports how we modified and adapted lunar FoMs to apply to the unique conditions of asteroids and their available data sets. We demonstrate the new FoMs using our CI1 simulant.

Eight Figures of Merit: We developed eight FoMs compared to lunar soil's four, as we judged these necessary to constrain vital characteristics of asteroid regolith.

Modal Mineralogy: following NASA's method, we measure bulk mineralogy of the simulant and compare to the reported bulk mineralogy of meteorites as samples of the targeted ateroid class. The reference material for the CI1 simulant is Orgueil measured by Bland et al. [7]. Each mineral abundance is listed in adjacent columns and the lesser of the two values is selected for each row then summed. A perfect match would sum to 100%, or FoM $\Phi_M=1$. The phyllosilicates in Orgueil are often reported as saponite and serpentine, but this is not precise and terrestrial versions of the minerals do not match properties of Orgueil adequately to produce, for example, the desired volatile releasae patterns. Therefore we found it necessary to lump phyllosilicates together in this FoM and create a new FoM specifically to grade volatile release patterns. Several additional decisions like this were required and will be reported in detail in a later publication. The tabulated mineralogical data are shown in Fig. 1. The calculated $\Phi_M=0.83$ for CI1 simulant compares well to the lunar simulants, which scored between 0.35 and 0.55.

Mineral	Target	Simulant	FoM Score
Serpentine/Saponite Phyllosilicates	67.93%	62.00%	0.6200
Equivalent Fayalite $FeSiO_4$	1.20%	0.70%	0.0070
Equivalent Forsterite $MgSiO_4$	5.64%	6.30%	0.0564
Magnetite Fe_3O_4	9.22%	13.50%	0.0922
Equivalent FeS	5.80%	0.000%	0.0000
Equivalent FeS_2	0.48%	6.50%	0.0048
Ferrihydrite $(Fe3+)_2O_3$•$0.5H_2O$	4.75%	0.00%	0.0000
Epsomite $MgSO_4$*$7H_2O$	0.00%	6.00%	0.0000
Organics	5.00%	5.00%	0.0500
TOTAL			0.8303

Figure 1. Calculation of Mineralogical FoM for CI1 simulant.

Elemental Composition: some compromises were necessary in designing the simulant, such as the choice to not use pyrrhotite as it is unstable in powder form. To motivate and score the selection of substitutes we developed an Elemental FoM Φ_E. Elemental composition is important, for example, for technologists developing radiation shielding from asteroid regolith, because cosmic radiation responds to the elements without regard for their crystalline structure. Substituting pyrite for pyrrhotite, while adjusting iron composition in other phases, can achieve high elemental fidelity. The resulting score for our CI1 simulant is $\Phi_E=0.94$.

Particle Size Distribution: NASA's method for particle sizing Φ_{PSD} is similar to the Φ_M and Φ_E, but uses %wt of binned particle size ranges for the rows in the table. Particle size information from asteroids is inadequately constrained for this. Instead of using a reference sample we created a reference model, which will have configuration control and can be revised as new data become available. As primary input for the model we rely on four disrupted asteroids that were observed and reported in the literature, their released clouds constrained by the size distributions used in the reported computer simulations. They are P/2010 A2 (LINEAR) [8,9], P/2012 F5 (Gibbs) [10], 596 Scheila [11,12], and a zodiacal dust band possibly associated with the Emilkowalski cluster [13]. The consensus is that the distributions are power laws with differential index approximately $q = -3.5$, which is the value for collisional equilibrium predicted by Dohnanyi [14]. The zodiacal band is reported somewhat coarser at -3.1 but is millions of years older and possibly coarsening through fines removal [13]. The maximum and minimum sizes reported for these clouds vary with parent body sizes, larger bodies having finer particles. Our reference model for asteroid simulant is to simply use a $q = -3.5$ differential power law and leave it to simulant users to sieve out the finer or coarser end of the spectrum to represent the size of asteroid they wish to simulate. A further consideration is that the size distribution measured in the Itokawa sample returned by Hayabusa suggest a different power index for the surficial material on an asteroid. We combined the statistics for the two parts of the returned sample, which had been fractionated via handling after return to Earth, as shown in Fig. 2, and we find index -1.5 cumulative or $q = -2.5$ differential. This suggests (as has been hypothesized by several) that winnowing at the surface removes fines, coarsening a thin exposed layer.

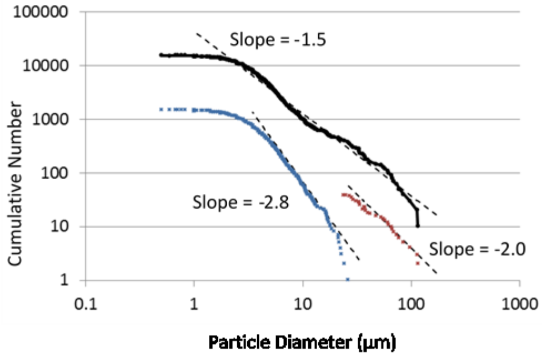

Figure 2. Combined cumulative size distribution of Itokawa particles. Blue and red fractions and their fitting slopes follow Tsuchiyama et al. [15]. Black is these two combined, moved higher ×10 for clarity.

We must decide whether to create multiple versions of simulant for surficial versus bulk particle sizing. One option is that users can purchase the cobble version of the simulants and crush it into whatever size distribution they require. We are currently in the process of finalizing values for Φ_{PSD}.

Volatile Release Pattern: We measured the thermogravimentric curve for the CI1 simulant and compare it with Orgueil as measured by [15], shown in Fig. 3.

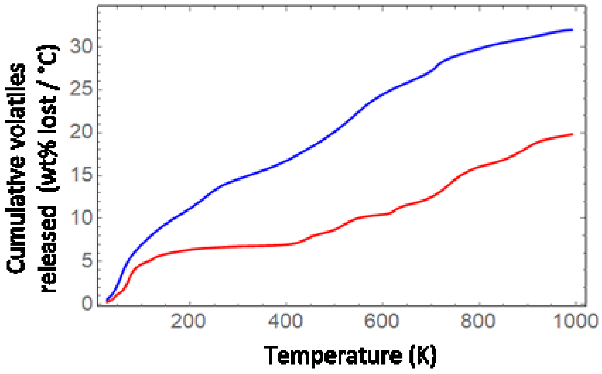

Figure 3. Cumulative volatile release for Orgueil in blue and for the CI simulant in red.

We define the FoM as the integral of the absolute value of the difference of these curves divided by the integral of the Orgueil curve, then subtracted from one. The FoM is Φ_{VR}=0.53. We developed another version of CI1 simulant with higher Φ_{VR}, to be reported later.

Other Figures of Merit: We developed similar FoMs for Mineral Grain Density, Cobble Bulk Density, Magnetic Susceptibility, and Cobble Mechanical Strength, which are being measured. Preliminary measurements show 8 mm dia.×76 mm tall cylindrical cobbles have 2.1 MPa compressive strength, comparing to a model of similarly sized Orgueil at 2.5 MPa.

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