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Figure of Merit for Asteroid Regolith Simulants

P. Metzger (1), D. Britt (1), S. Covey (2) and J.S. Lewis (2)
(1) University of Central Florida, USA (philip.metzger@ucf.edu), (2) Deep Space Industries, USA and Luxembourg.

Abstract

Asteroid regolith simulant is being developed for several asteroid classes. These simulants are shown to have very high fidelity to the reference meteorites in terms of mineral and elemental composition. Particle sizes and other characteristics are also being validated.

1. Introduction

Simulated asteroid regolith, or *asteroid simulant*, is needed for tests of space mining, propellant manufacturing, radiation shielding, and more. In 2015, NASA selected Deep Space Industries in partnership with the University of Central Florida to develop several asteroid simulants. Geological processes on asteroids are different than those operating on Earth so it is impractical to create simulants that replicate all characteristics of actual asteroids. Learning from the experiences of the lunar exploration community [1], we held a workshop October 6-7, 2015 to select the subset of those properties that would control the design of the simulants [2]. The workshop also chose which spectral class asteroids will be simulated: CI, CM, CR, C2, CV, and an L-Chondrite Ordinary. The CI simulant has now been developed and is reported here, while the others are in development [3].

It is important that members of the user community understand the limitations of any simulant. Here, we present a Figure of Merit (FoM) system based on NASA's lunar simulant program [4]. A simulant with a high FoM for mineralogical fidelity may be good for resource processing tests, while a simulant with a high FoM for geotechnical fidelity may be better for a mining mechanics test. The FoM is calculated by measuring particle size distribution, mineralogical composition, volatile inventory, and other properties of the simulant then mathematically comparing these results to the best available estimates of the same properties on asteroids.

2. Control Parameters

The workshop identified 65 properties of asteroid materials including grain properties, electrostatics and magnetics, geomechanics, optical properties, gas interactions, thermal and physical properties, chemical reactivity, texture, and volatile inventory. Of these, the following were chosen to be "control parameters" for simulant design: particle size distribution, magnetic susceptibility, tensile and compressive strength of cobbles, shear strength of regolith, bulk density and porosity of cobbles, mineralogical composition, water content, organic content, sulfur compounds, and volatile release patterns in temperature and pressure.

3. Mineral /Elemental Composition

The CI simulant is the first one developed. It is based on the mineralogy analysis of the Orgueil meteorite by Bland, et al [5]. It was made with minerals obtained from commercial suppliers and mines in various locales. In some cases, the minerals or volatiles in the actual meteorite are unstable (e.g., pyrrhotite and troilite) or unsafe for human exposure (polycyclic aromatic hydrocarbons in the insoluble organic material) so substitutions were made (pyrite for the iron sulfides, sub-bituminous coal for the organics). These substitutes were selected for reasonable chemical similarity and for elemental similarity. The olivine grains in Orgueil vary in Mg-Fe composition but are generally nearer the fayalite end member, so we have chosen Fo_{90} to match the bulk average composition. The phyllosilicates in Orgueil are a disordered serpentine-saponite mixture. We have chosen antigorite, vermiculite, and attapulgite clays for chemical similarity, to provide the correct volatile inventory, and to have realistic volatile thermal release patterns. We substituted the iron hydrate ferrihydrite with the magnesium hydrate epsomite since the former is commercially unavailable but the latter will approximate the water's thermal release pattern, and the net Mg and Fe abundances are still close to the targets.

Deep Space Industries is making the simulant available in several forms, including (1) regolith, (2) slabs and cobbles, (3) ready-to-prepare dry mix, and bagged un-mixed source materials. Here we discuss the completed regolith version. The minerals were crushed, mixed, wetted, and dried in a method described by Covey, at al [3] to create cobbles that are then re-crushed into multi-mineralic particles with the desired power law size distribution. The fidelity of the chemical composition is quantified by two FoMs, one for mineralogy and the other for elemental abundance.

4. Figure of Merit Calculations

We follow the FoM method developed by NASA for lunar soil simulants [4]. The method is to list in adjacent columns the mass percent of each component for the reference meteorite ("target") and the simulant and to take the lesser of these two values. These are summed. This calculates the "overlap" in compositional percentages. The Mineralogical FoM for the CI simulant is shown in Figure 1.

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. Mineralogical FoM for CI simulant.

This compares very well with the scores for lunar simulants. The highest scoring, available lunar simulant, NU-LHT-2M, has a score of 0.55, while the widely used JSC-1A has a score of 0.35.

In addition to the mineralogical FoM, we have calculated an elemental FoM. Elemental composition is important for radiation shielding studies, for example. The results are shown in Figure 2.

Element	Target	Simulant	FoM Score
Fe	18.95%	16.24%	0.162438
Si	10.64%	11.18%	0.1064
Mg	9.62%	13.54%	0.0962
S	5.25%	4.19%	0.041944
C	3.22%	3.85%	0.03215
H	2.02%	1.67%	0.016743
Al	0.65%	1.14%	0.00645
Ni	1.00%	0.15%	0.001538
Ca	0.87%	1.50%	0.00865
Na	0.55%	0.04%	0.000355
N	0.12%	0.05%	0.000497
Cr	0.24%	0.03%	0.000273
Mn	0.17%	0.03%	0.000288
P	0.13%	0.04%	0.000375
O and traces	46.62%	46.34%	0.463426
Total Score			0.937727

Figure 1. Elemental FoM for CI simulant.

5. Additional Measurements

Particle size distribution, magnetic susceptibility, water release patterns, and other characteristics of the regolith are also being measured and will be reported. Simulants for the other asteroid classes are also in development.

References

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