Measuring the fidelity of asteroid regolith simulants


1The Florida Space Institute, UCF, Orlando, FL 32826. Email: philip.metzger@ucf.edu. 2University of Central Florida, Department of Physics, Orlando, FL 32816. 3The Center for Lunar and Asteroid Surface Science, University of Central Florida, Orlando, FL 32816. 4Deep Space Industries, 6557 Hazeltine National Dr., Orlando, FL 32822. Engineering and Technology Directorate, NASA Kennedy Space Center, 32899.

Asteroid Simulants Program

UCF and Deep Space Industries are working with the NASA KSC Swamp Works to create a family of high-fidelity asteroid simulants, both “meteorite” (cobbles) and regolith, based on the properties of meteorites. We started with the following five simulants:

<table>
<thead>
<tr>
<th>Simulant (Asteroid Class)</th>
<th>Selected Reference Material (Meteorite)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI</td>
<td>Orgueil</td>
</tr>
<tr>
<td>CM</td>
<td>Marchis</td>
</tr>
<tr>
<td>C2</td>
<td>Tagish Lake</td>
</tr>
<tr>
<td>CR</td>
<td>Average of five Antarctic finds: GRA 95229, LAP 02242, QUE 99177, PCA 91082, and GRA 06100</td>
</tr>
<tr>
<td>CV</td>
<td>Allende</td>
</tr>
</tbody>
</table>

Examples of Source Materials

We obtained source materials to create the simulants from a variety of mines and commercial suppliers.

- Antigorite
- Vermiculite
- Smectite
- Magnesite
- Olivine (Fo90)
- Pyrite
- Epsomite
- Bituminous Coal

Processing to Create Polymorphic Cobbles and Grains

- Crushing
- Sieving
- Mixing (mixed powder)
- Wetting
- Stiff mixture
- Drying
- Recrushing
- Polymorphic grains

Dried slabs & cobbles

Figure ofMerit (FoM) Protocol

We adapt the protocol NASA developed for grading lunar soil simulants. We take measurements of selected properties of both the asteroid simulants and corresponding reference meteorites. A 2016 workshop selected the properties based on community needs. We mathematically compare the measurements (similar to vector dot products) to tell how far each simulat is from the corresponding meteorite property. This produces a set of numbers between 0 and 1 for each property of each simulat, which are the Figures ofMerit (FoMs). The set of FoMs informs the “Fit-To-Use” table (still being developed) that tells how good each simulat is for each type of test, such as spectroscopy, mining, or water extraction tests.

Here we report results for the CI Simulant to evaluate the FoM protocol.

1 & 2: Mineralogical and Elemental, $\Phi_M$ & $\Phi_E$

For mineralogical FoM $\Phi_M$, it was necessary to treat phyllosilicates as a single category because they are inadequately constrained in Orgueil. We created a Volatile Release FoM (below) to better constrain the most desired phyllosilicate property.

<table>
<thead>
<tr>
<th>Mineral/Material</th>
<th>Ref. 1. Orgueil mass fraction</th>
<th>Simulant mass fraction</th>
<th>FoM Calculation $min(r_i, s_i)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined Phyllosilicates</td>
<td>0.6793</td>
<td>0.6200</td>
<td>0.6200</td>
</tr>
<tr>
<td>Equivalent Faralite FeSiO3</td>
<td>0.0120</td>
<td>0.0070</td>
<td>0.0070</td>
</tr>
<tr>
<td>Equivalent Forsterite MgSiO3</td>
<td>0.0564</td>
<td>0.0630</td>
<td>0.0564</td>
</tr>
<tr>
<td>Magnetite Fe3O4</td>
<td>0.0922</td>
<td>0.1350</td>
<td>0.0922</td>
</tr>
<tr>
<td>Equiv. FeS</td>
<td>0.0580</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Equiv. FeS2</td>
<td>0.0048</td>
<td>0.0650</td>
<td>0.0048</td>
</tr>
<tr>
<td>Ferrhydrite Fe(3)xOy*0.5H2O</td>
<td>0.0475</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>Episotopy MgSiO3*7H2O</td>
<td>0.0000</td>
<td>0.0660</td>
<td>0.0000</td>
</tr>
<tr>
<td>Organics</td>
<td>0.0500</td>
<td>0.0500</td>
<td>0.0500</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1.000</td>
<td>1.000</td>
<td>0.83</td>
</tr>
</tbody>
</table>

We use the same method for elemental FoM $\Phi_E$, comparing measured elemental composition of the Orgueil meteorite to stoichiometric calculations from the chemical formulas of simulant source materials. This finds $\Phi_E = 0.94$.

3: Particle Size Distribution, $\Phi_{PSD}$

For particle sizing FoM we cannot use meteorites so we develop a reference model. Data suggest asteroid surfaces may be coarsened by fines loss in solar wind/photonization. Here we focus on bulk release based on recently disrupted asteroids (table). $D_{min}$ and $D_{max}$ vary; users would need to amend the simulat to match an asteroid. Power indices are near Dohnanyi’s theoretical $q^R - 3.5$, which we choose for the model. We write a power law for the particle count, convert it to “Mass-Finer-Than”, and perform least squares fit to the simulat data (see plot), finding $q^P = 2.5$, $D_{min} = 1.0$ μm, and $D_{max} = 105$ μm. Until a better reference model is available, we define $\Phi_{PSD} = q^P = 0.96$.

4: Volatile Release, $\Phi_{VR}$

For reference we use thermogravimetric analysis (TGA) of Orgueil by King et al. and we perform TGA for the simulat.

5: Compressive Strength, $\Phi_{CS}$

Tsuchiya et al. (2008) measured 3.1 MPa for S0-200 μm samples of Orgueil. No other Orgueil strength measurements are available. Scaling this via Weibull theory and tensile/compressive correlation predicts $\rho_{bulk} = 2.5$ MPa compressive strength for a 4.4 cm cube sample of Orgueil, the same volume as our measurements.

For the CI simulat we performed standard ASTM C39/C93M-17b tests using an MTS Criterion Model 43 on four specimens and obtained $\rho_{bulk} = 1.7$ ± 0.5 MPa. For the CI simulat we performed standard ASTM C39/C93M-17b tests using an MTS Criterion Model 43 on four specimens and obtained $\rho_{bulk} = 1.7$ ± 0.5 MPa.

6: Meteorite Density, $\Phi_D$

For reference we use the measurements of Orgueil by Consolmagno and Britt, $\rho_{bulk} = 1.58 ± 0.03$. We measure the simulat cobble density and find $\rho_{bulk} = 1.60 ± 0.01$. Using a method like $\Phi_{CS}$ but non-logarithmic we find,

$$\Phi_D = \frac{1}{\rho_{bulk}} \left[ \frac{\rho_{min} - \rho_{bulk}}{0.5 \rho_{bulk}} \right] = 0.72$$

7: Magnetic Susceptibility, $\Phi_{MS}$

Following a similar method as for $\Phi_{CS}$, we use measurements of Orgueil fro Refs. 8, mass-weighting published results to find $\chi = 4.81 \times 10^{-8}$. We used a Faraday Scale for the simulat and found $\log_{10} \chi^{R} = 4.78$. We used a Faraday Scale for the simulat and found $\log_{10} \chi^{R} = 4.78$.

$$\Phi_{CS} = \max\left\{ 0, 1 - \frac{\delta \chi}{\log_{10} \chi^{R}} \right\} = 0.77$$

Summary

The mineralogical FoM (0.83) reflects the asteroid simulat is higher mineralogical fidelity than available lunar soil simulats (0.28 – 0.55). Volatile release FoM supplements mineralogical FoM due to uncertainties in meteorite phyllosilicates. The particle Sizing FoM cannot be more specific until better reference data are available, so it only quantifies power index. These seven FoMs adequately quantify the fidelity of the simulat’s behaviors for many tests needed by the user community. Future work will measure FoMs for the other asteroid spectral class simulats under development.

References