Asteroid Regolith Model and Figure of Merit for Asteroid Simulants

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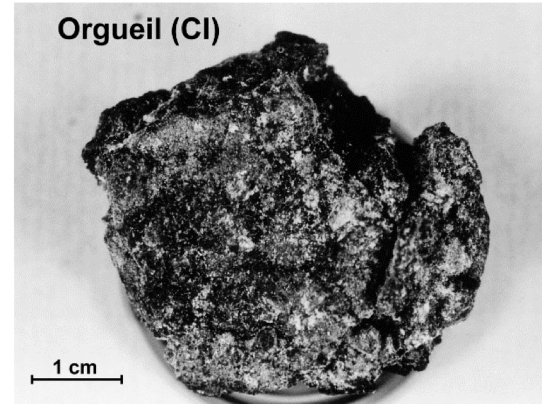
Asteroid Regolith Simulants

- **CLASS partnered with Deep Space Industries (DSI) to develop a family of asteroid regolith simulants for engineering and ISRU development.**
- **Under a Phase II SBIR funding we developed and are producing a total of 5 simulants: CI, CM, CR, CV, and C2**
  - **We used the type meteorites as a guide to mineralogy, strength properties, and volatile release patterns**
  - **We used a variety of data sources as a guide to particle sizing.**
- **We have also developed Mars & Phobos simulants based on rover mission data and two theories of Phobos formation**



Asteroid simulant Source Minerals (examples)

Antigorite

Vermiculite

Smectite

Magnetite

Olivine (Fo90)

Pyrite

Epsomite

Bituminous Coal

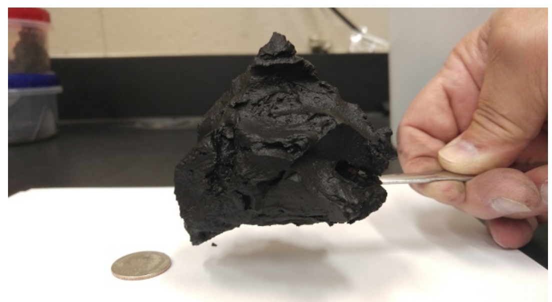
Processing

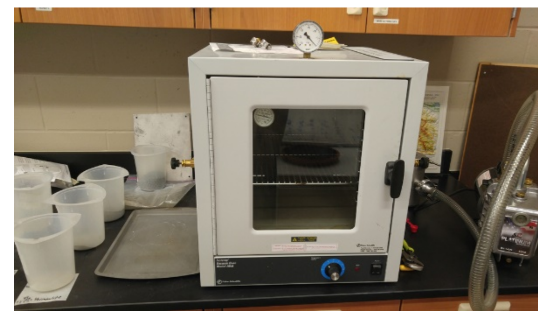
Crushing

Sieving


Mixing (mixed powder)


Wetting


Stiff mixture


Drying


Dried slabs & cobbles

Recrushing


Polymineralic grains

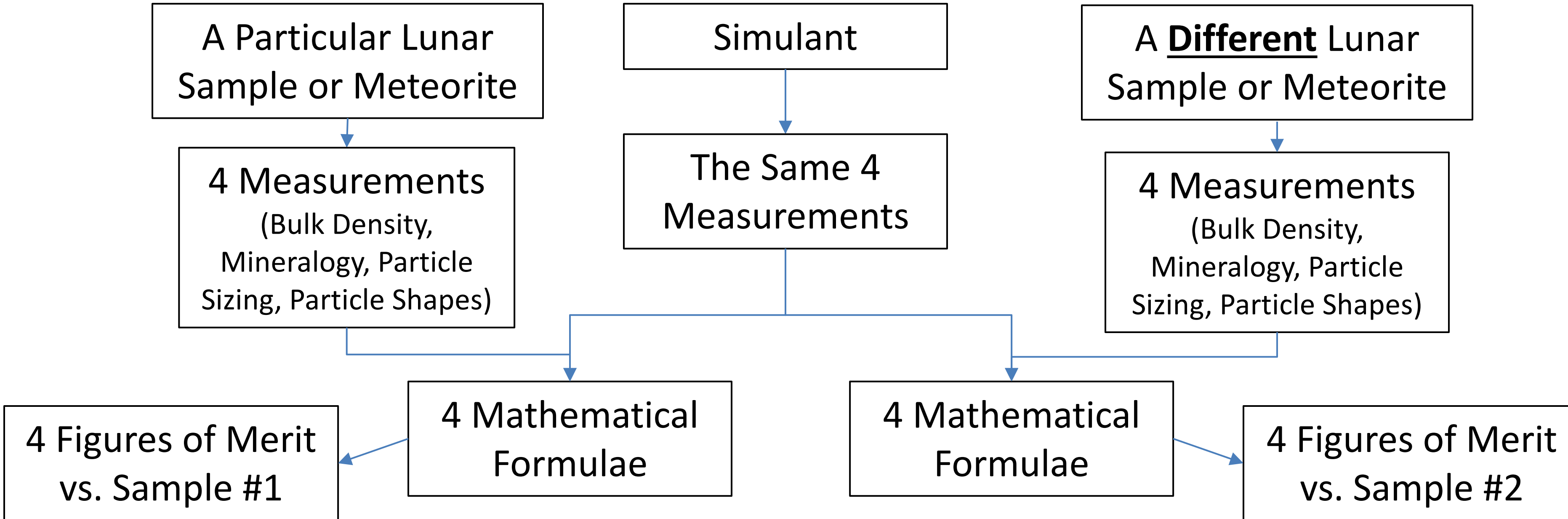
Properties of Lunar Simulants

- The Lunar Community created a list of 32 desired properties and organized them into ten categories
- Far too difficult and expensive to create a simulant with all of the desired properties.
  - Extraterrestrial regolith is too exotic
- The lunar community focused on just **<u>three</u>** properties or groups of properties:
  - the particle size distribution,
  - the mechanical properties,
  - the chemical properties

The Lunar Simulant Experience

- An explosion of >30 simulants by 2010, usually with no pedigree
- Researchers often used inappropriate simulants in their tests
  - E.g., use merely <u>physical</u> simulants for <u>chemical</u> tests
  - This was despite the outcry from lunar scientists
- NASA set up a simulants team at MSFC to reestablish sanity
- NASA developed a "Figure of Merit" system to evaluate and communicate the fidelity of simulants for various purposes

NASA's Process for Simulants



Fit-to-Use Table

	Mining Lunar Highlands	Mining Lunar Mare	Chemical Extraction from Highlands	Chemical Extraction from Mare	Etc.
Simulant #1	X	X	X		
Simulant #2	X	X			
Simulant #3		X		X	
Simulant #4			X		
Simulant #5	X			X	
Simulant #6			X		
Simulant #7				X	
Simulant #8	X	X			
Simulant #9	X	X			
Simulant #10			X		

Selected Properties for FoMs

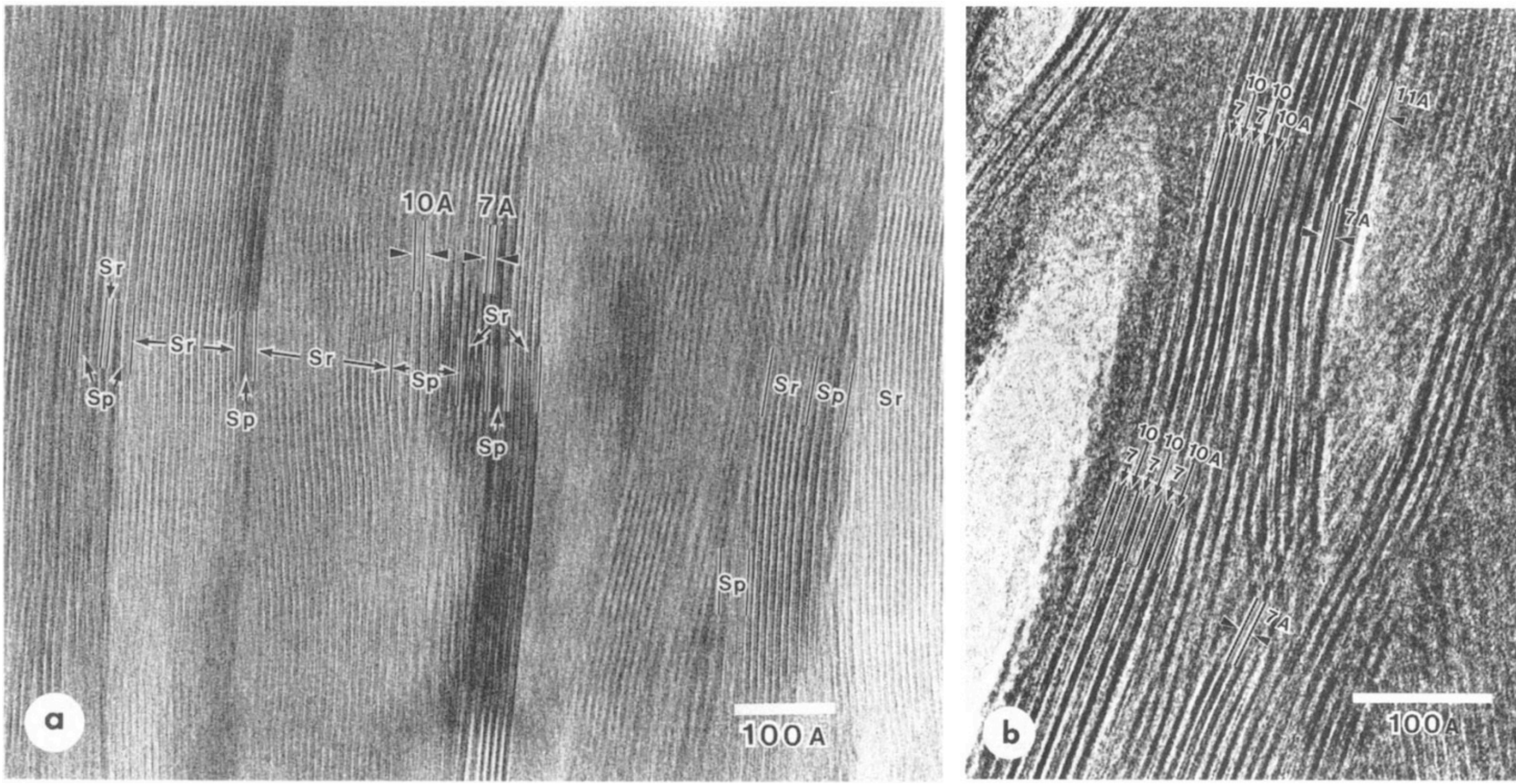
- NASA used four Figures of Merit for each lunar reference sample:
  - Mineralogy FoM,
  - Particle Sizing FoM
  - Particle Shapes FoM
  - Bulk Density FoM
- We developing eight for asteroid simulant

MINERALOGICAL FOM

Recipe for the CI Asteroid Simulant

Mineral/Material	wt%
Antigorite $(Mg,Fe^{2+})_3Si_2O_5(OH)_4$	48.0
Vermiculite $(Mg,Fe,Al)_3(Al,Si)4O_{10}(OH)_2\times 4(H_2O)$	9.0
Attapulgite $(Ca,Na)_{0.33}(Mg_{2.66},Li_{0.33})Si_4O_{10}(F,OH)_2\times 4H_2O$	5.0
Olivine Fo90 $(Mg_{0.9},Fe_{0.1})2SiO_4$	7.0
Magnetite Fe_3O_4	13.5
Pyrite FeS_2	6.5
Epsomite $MgSO_4\times 7H_2O$	6.0
Sub Bituminous coal	5.0
TOTAL	**100.0**

Interstratified Phyllosilicates in Orgeuil Meteorite



Credit: Tomeoka & Buseck, 1988

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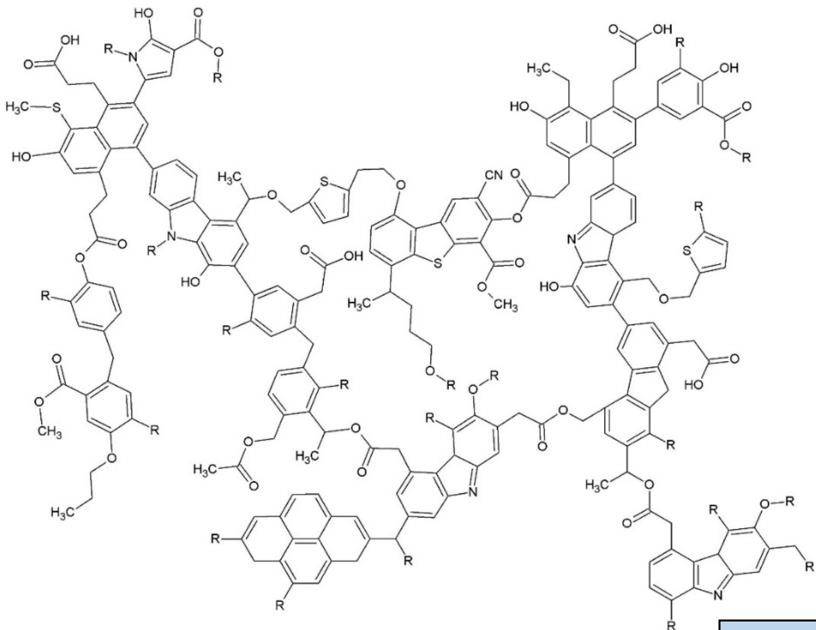
Organics



Sylvie Derenne and François Robert, *Meteoritics & Planetary Science* 45, Nr 9, 1461–1475 (2010), Meteorite macromolecule indicated for Murchison.

		Meteorite (type) Aromaticity (%)			
		EET92042 (CR2)	Orguiel (CI1)	Murchison (CM2)	Tagish Lake (C2)
Coal Grade	**Aromaticity (%)**	48 - 52	61 - 65	62 - 66	79 – 83
Lignite	49	X			
Sub-bituminous	60-73		X	X	
Bituminous	62-80				X
Semi-anthracite	85				
Anthracite	91				

Mineralogical FoM

Mineral/Material	Orgueil mass fraction r_i	Simulant mass fraction s_i	FoM Calculation $\min(s_i, r_i)$
Combined Phyllosilicates	0.6793	0.6200	0.6200
Equivalent Fayalite $FeSiO_4$	0.0120	0.0070	0.0070
Equivalent Forsterite $MgSiO_4$	0.0564	0.0630	0.0564
Magnetite Fe_3O_4	0.0922	0.1350	0.0922
Equivalent FeS	0.0580	0.0000	0.0000
Equivalent FeS_2	0.0048	0.0650	0.0048
Ferrihydrite $(Fe^{3+})_2O_3 \times 0.5H_2O$	0.0475	0.0000	0.0000
Epsomite $MgSO_4 \times 7H_2O$	0.0000	0.0600	0.0000
Organics	0.0500	0.0500	0.0500
TOTAL	1.00	1.00	$\mathbf{\Phi_M = 0.83}$

Comparing Mineralogical FoMs

Simulant	Reference Material	Figure of Merit
UCF/DSI-CI-2	Orgueil	0.83*
NU-LHT-1M	Lunar 64001/64002	0.65
NU-LHT-2M	Lunar 64001/64002	0.55
OB-1	Lunar 64001/64002	0.28
JSC-1	Lunar 64001/64002	0.33
JSC-1A	Lunar 64001/64002	0.35
JSC-1AF	Lunar 64001/64002	0.43
MLS-1	Lunar 64001/64002	0.35
FJS-1	Lunar 64001/64002	0.36

ELEMENTAL FOM

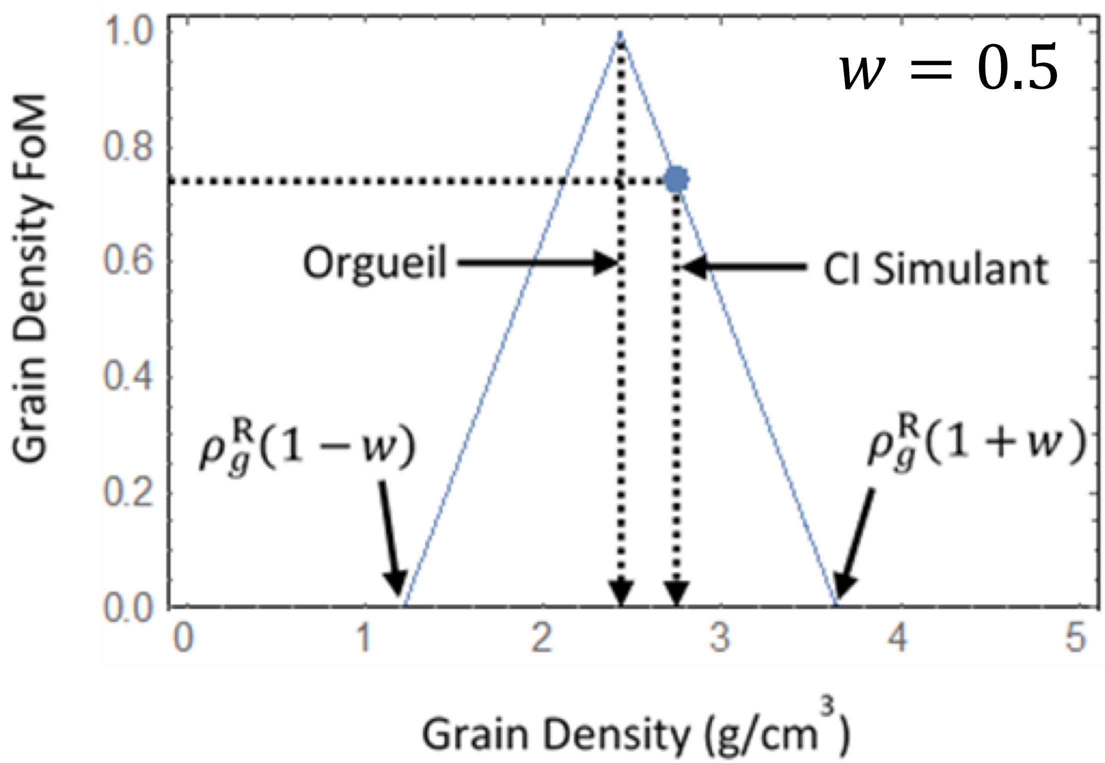
Elemental FoM

Element	Orgueil mass fraction v_i	Simulant mass fraction w_i	FoM Calculation $\min(v_i, w_i)$
Fe	0.1895	0.1624	0.1624
Si	0.1064	0.1118	0.1064
Mg	0.0962	0.1354	0.0962
S	0.0525	0.0419	0.0419
C	0.0322	0.0385	0.0322
H	0.0202	0.0167	0.0167
Al	0.0065	0.0114	0.0065
Ni	0.0100	0.0015	0.0015
Ca	0.0087	0.0150	0.0087
Na	0.0055	0.0004	0.0004
N	0.0012	0.0005	0.0005
Cr	0.0024	0.0003	0.0003
Mn	0.0017	0.0003	0.0003
P	0.0013	0.0004	0.0004
O and traces	0.4662	0.4634	0.4634
Total	1.0000	1.0000	$\boldsymbol{\Phi_E = 0.94}$

GRAIN DENSITY FOM

Grain Density FoM

$$\Phi_{\mathrm{D}} = \max\left\{0, 1 - \frac{1}{w}\frac{\left|\rho_g^{\mathrm{S}} - \rho_g^{\mathrm{R}}\right|}{\rho_g^{R}}\right\}$$

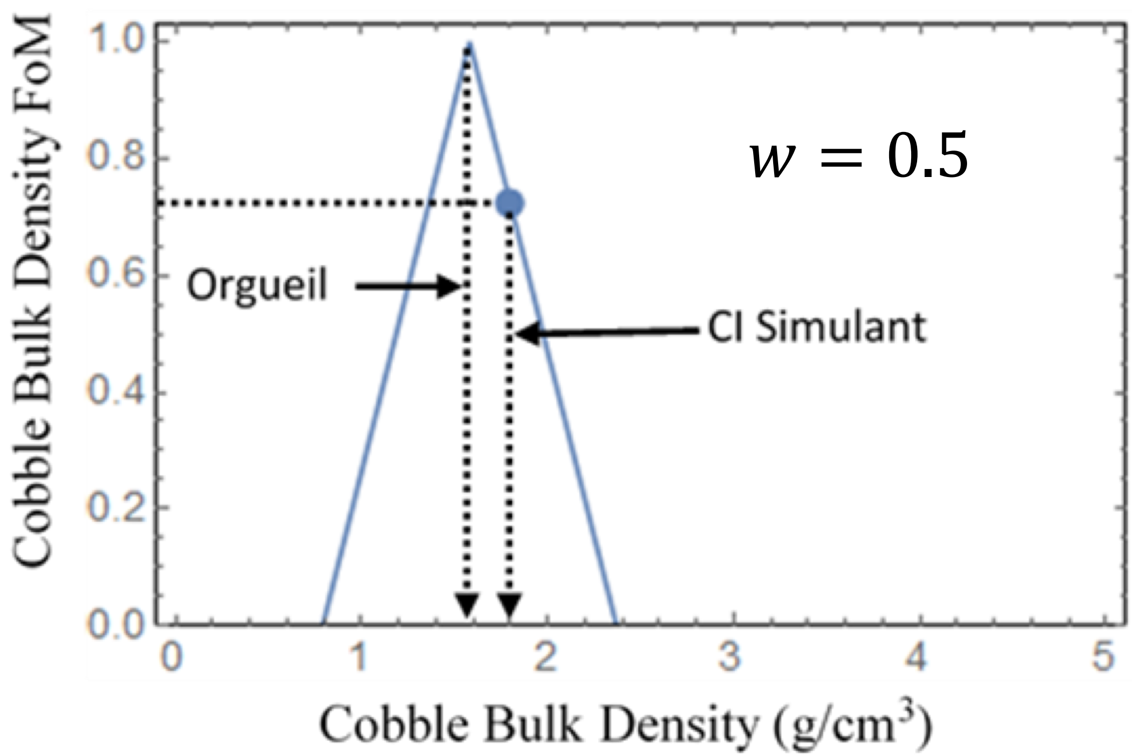


COBBLE BULK DENSITY FOM

Porosity Reduces Bulk Density

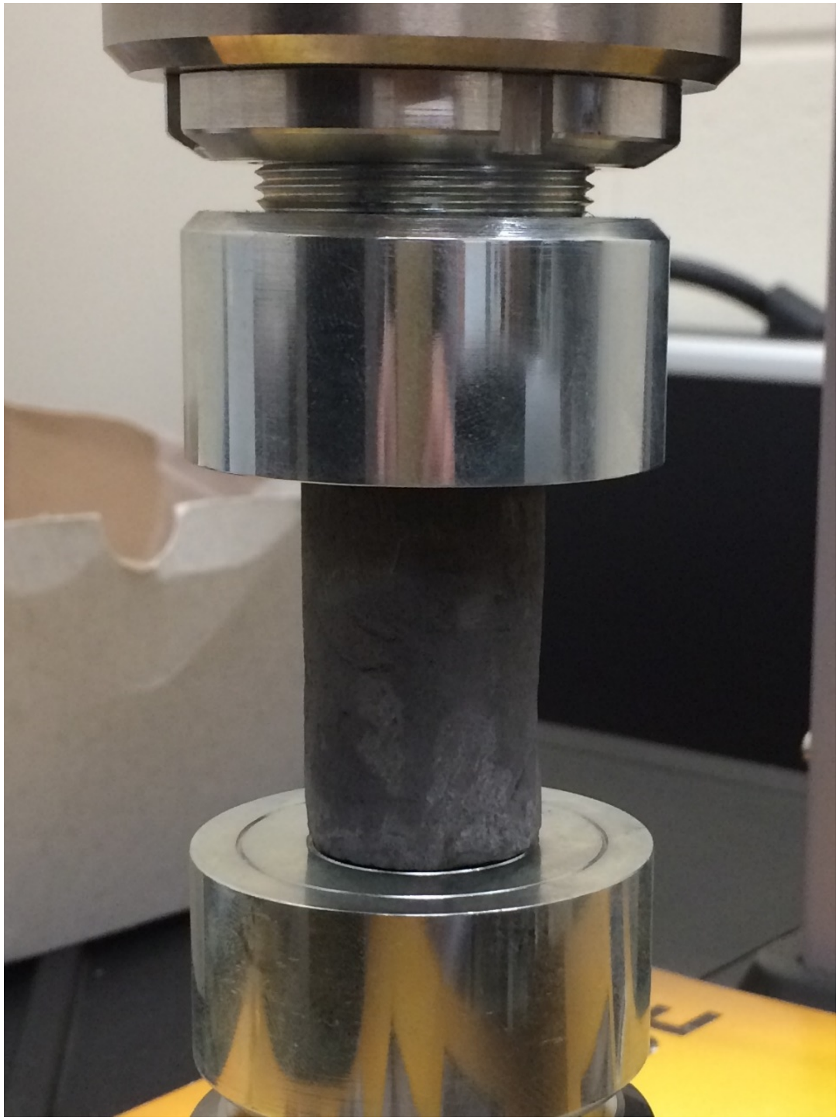
Cobble Bulk Density FoM

$$\Phi_{\mathrm{BD}} = \max\left\{0, 1 - \frac{1}{w}\frac{\left|\rho^{\mathrm{S}}_{\mathrm{bulk}} - \rho^{\mathrm{R}}_{\mathrm{bulk}}\right|}{\rho^{R}_{\mathrm{bulk}}}\right\}$$



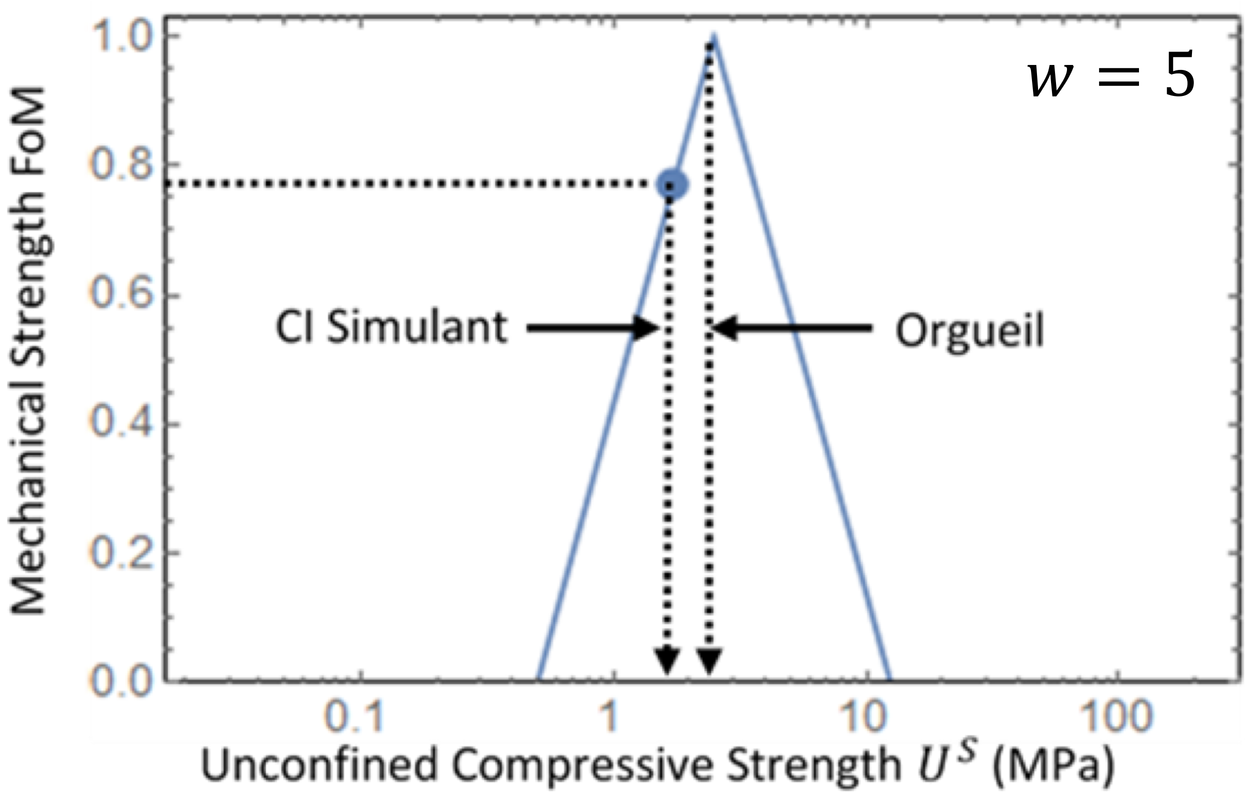
COBBLE MECHANICAL STRENGTH FOM

Unconfined Compression Tests



Cobble Mechanical Strength FoM

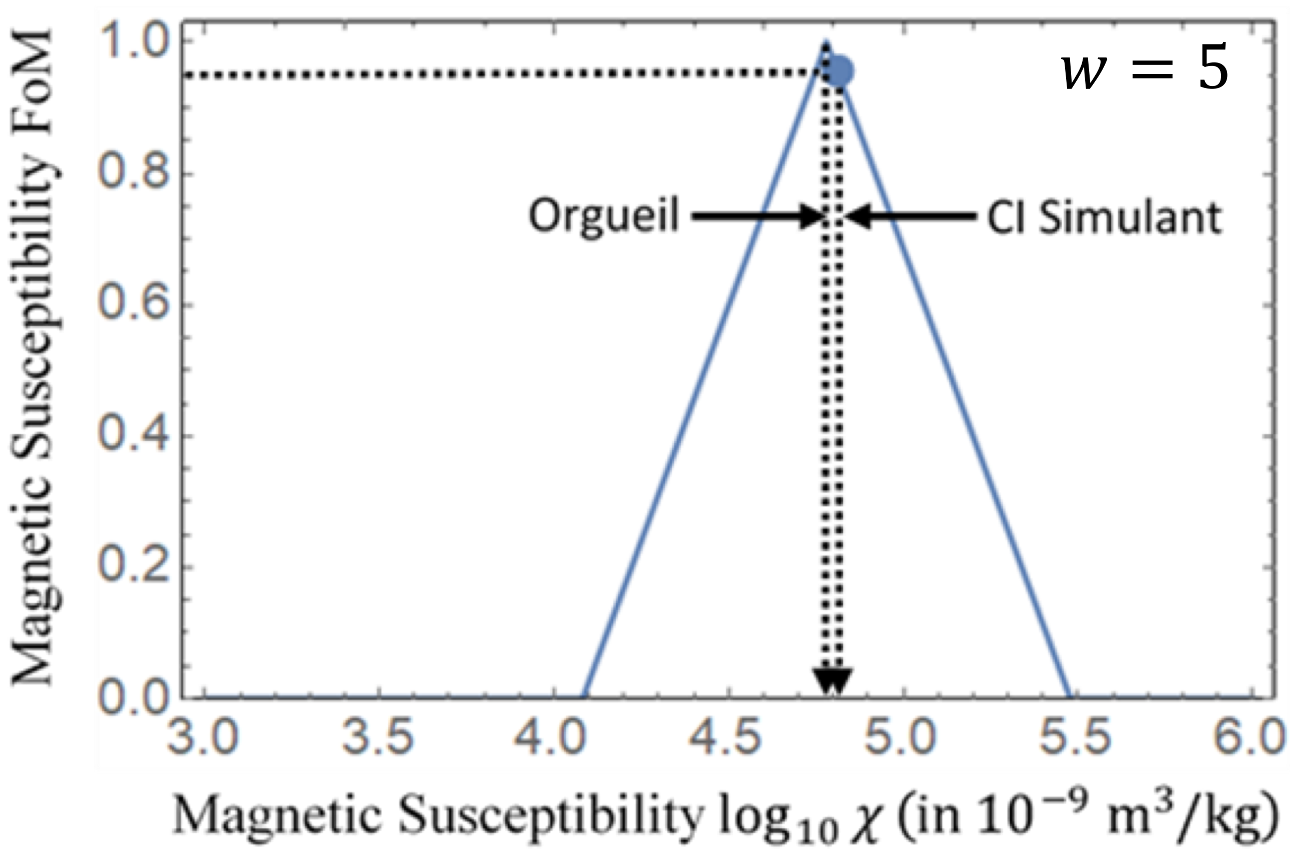
$$\Phi_{\mathrm{CS}} = \max\left\{0, 1 - \frac{\left|\log_{10} U^{\mathrm{S}} - \log_{10} U^{\mathrm{R}}\right|}{\log_{10} w}\right\} = \max\left\{0, 1 - \frac{\left|\log_{10}(U^{\mathrm{S}}/U^{\mathrm{R}})\right|}{\log_{10} w}\right\}$$



MAGNETIC SUSCEPTIBILITY FOM

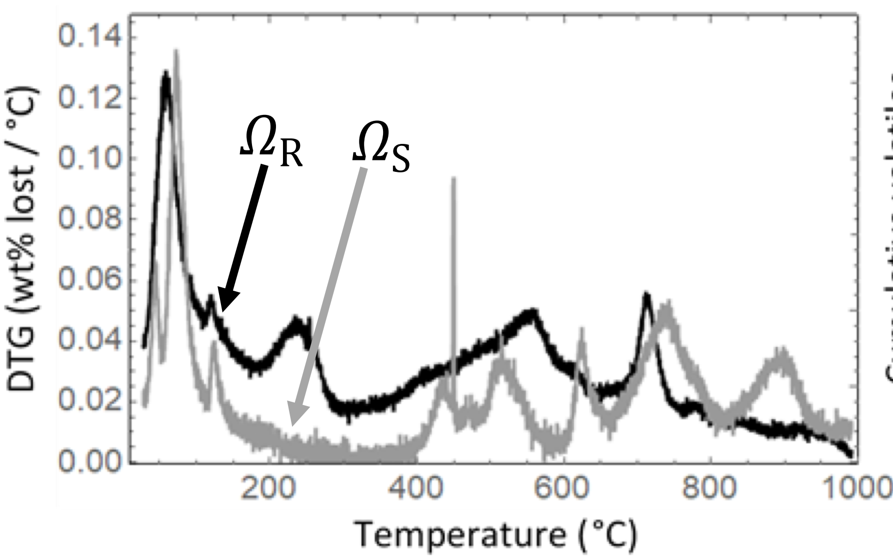
Magnetic Susceptibility FoM

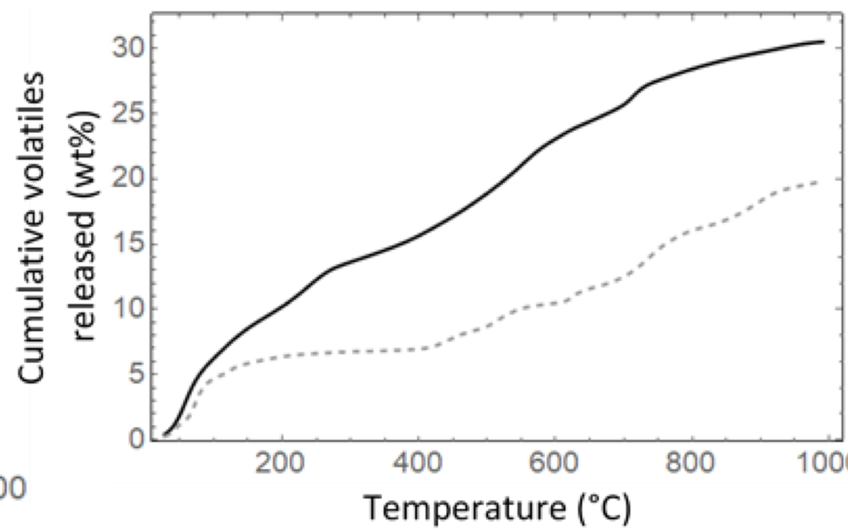
$$\Phi_{\text{MS}} = \max\left\{0, 1 - \frac{\left|\log_{10}(\chi^{\text{S}}) - \log_{10}(\chi^{\text{R}})\right|}{\log_{10} w}\right\} = \max\left\{0, 1 - \frac{\left|\log_{10}(\chi^{\text{S}}/\chi^{\text{R}})\right|}{\log_{10} w}\right\}$$



VOLATILE RELEASE FOM

Volatile Release Patterns

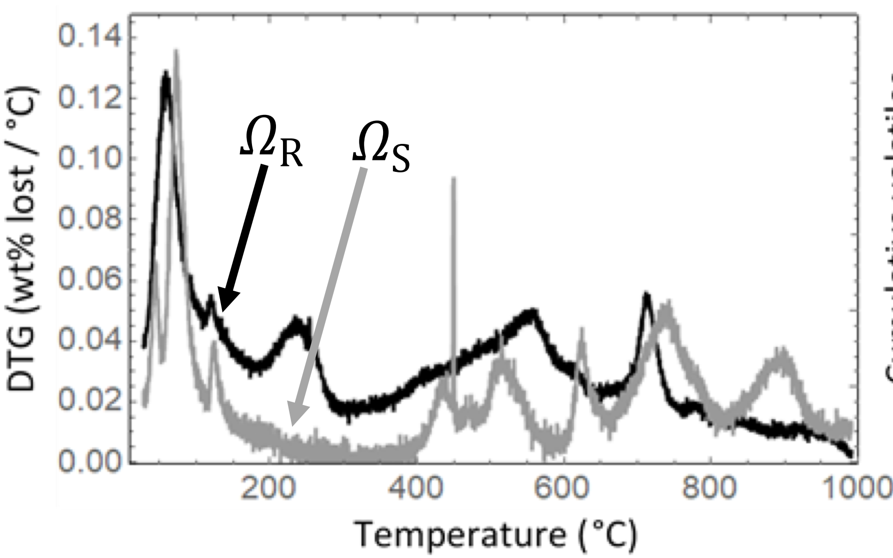


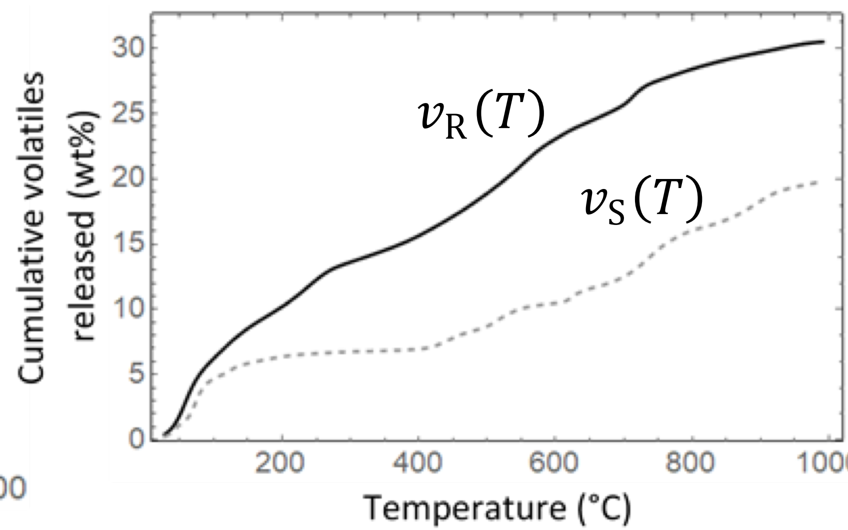


$$V_{\mathrm{S}} = \|\Omega_{\mathrm{S}}\|_1 = \int_{T_{\min}}^{T_{\max}} |\Omega_{\mathrm{S}}| \, \mathrm{d}T, \qquad V_{\mathrm{R}} = \|\Omega_{\mathrm{R}}\|_1 = \int_{T_{\min}}^{T_{\max}} |\Omega_{\mathrm{R}}| \, \mathrm{d}T$$

$$\delta\Omega = \|\Omega_{\mathrm{S}} - \Omega_{\mathrm{R}}\|_1 = \int_{T_{\min}}^{T_{\max}} |\Omega_{\mathrm{S}} - \Omega_{\mathrm{R}}| \, \mathrm{d}T. \qquad \Phi_{\mathrm{VR}}^{(1)} = \max\left\{0, 1 - \frac{1}{w}\frac{\delta\Omega}{V_{\mathrm{R}}}\right\}.$$

Volatile Release Patterns



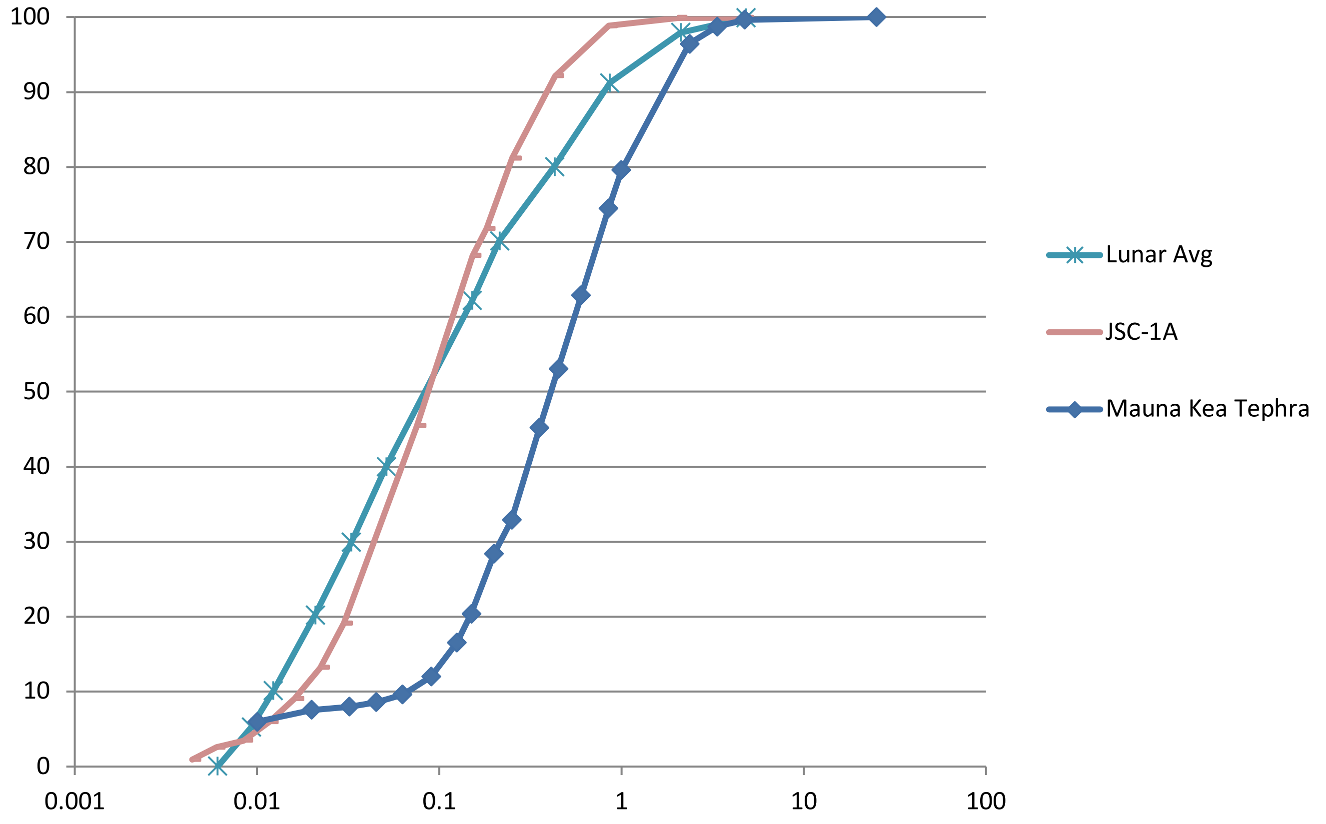


$$v_{\mathrm{S}}(T) = \int_{T_{\min}}^{T} |\Omega_{\mathrm{S}}(T')|\,\mathrm{d}T', \qquad v_{\mathrm{R}}(T) = \int_{T_{\min}}^{T} |\Omega_{\mathrm{R}}(T')|\,\mathrm{d}T'$$

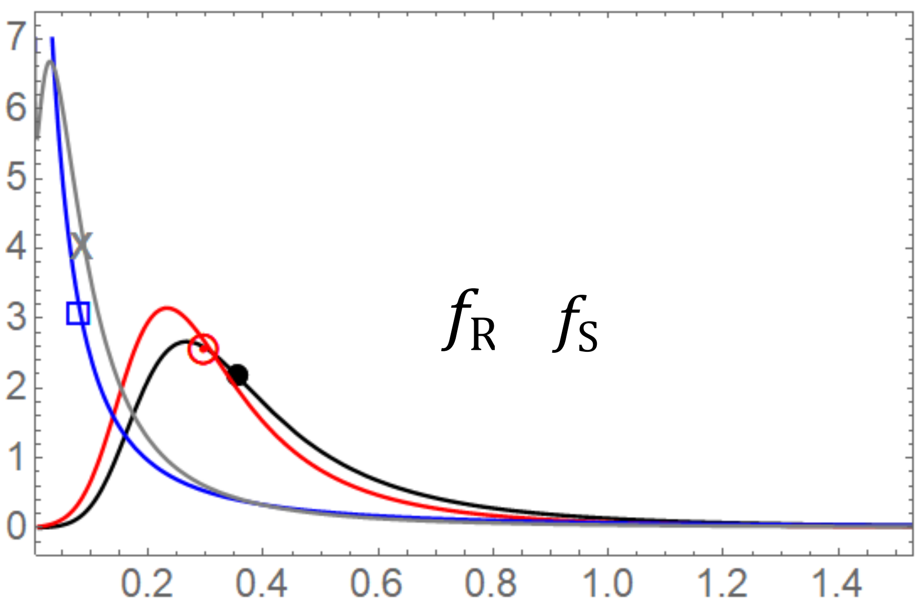
$$\delta v = \|v_{\mathrm{S}} - v_{\mathrm{R}}\|_1 = \int_{T_{\min}}^{T_{\max}} |v_{\mathrm{S}} - v_{\mathrm{R}}|\,\mathrm{d}T \qquad \Phi_{\mathrm{VR}} = \max\left\{0, 1 - \frac{1}{w}\frac{\delta v}{\|v_{\mathrm{R}}\|_1}\right\}.$$

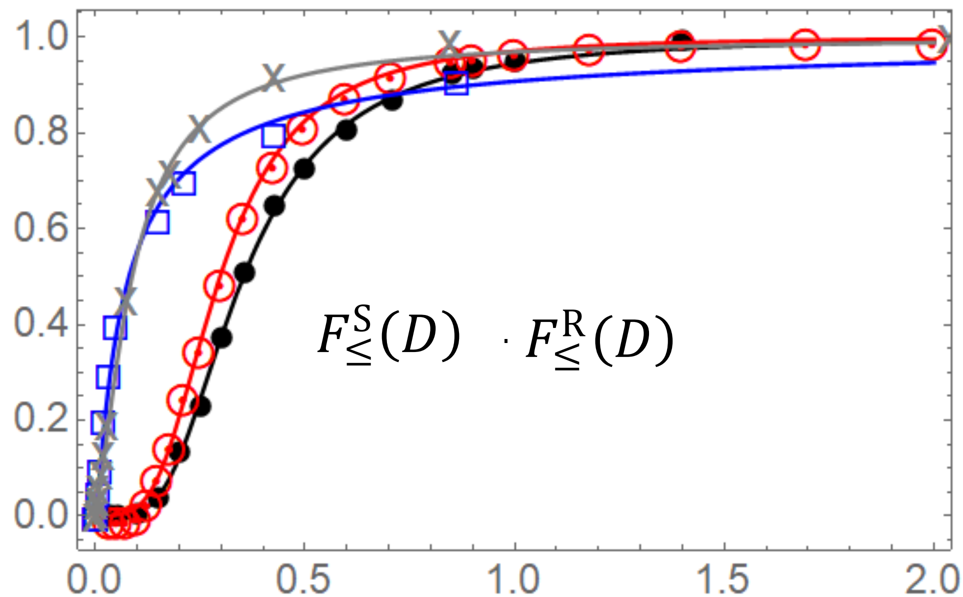
REGOLITH PARTICLE SIZE FOM

Lunar Soil Particle Size Distribution



How to Compare Size Distributions?





$$\Phi_{PSD} = \int_0^\infty \min(f_S, f_R)\,\mathrm{d}D$$

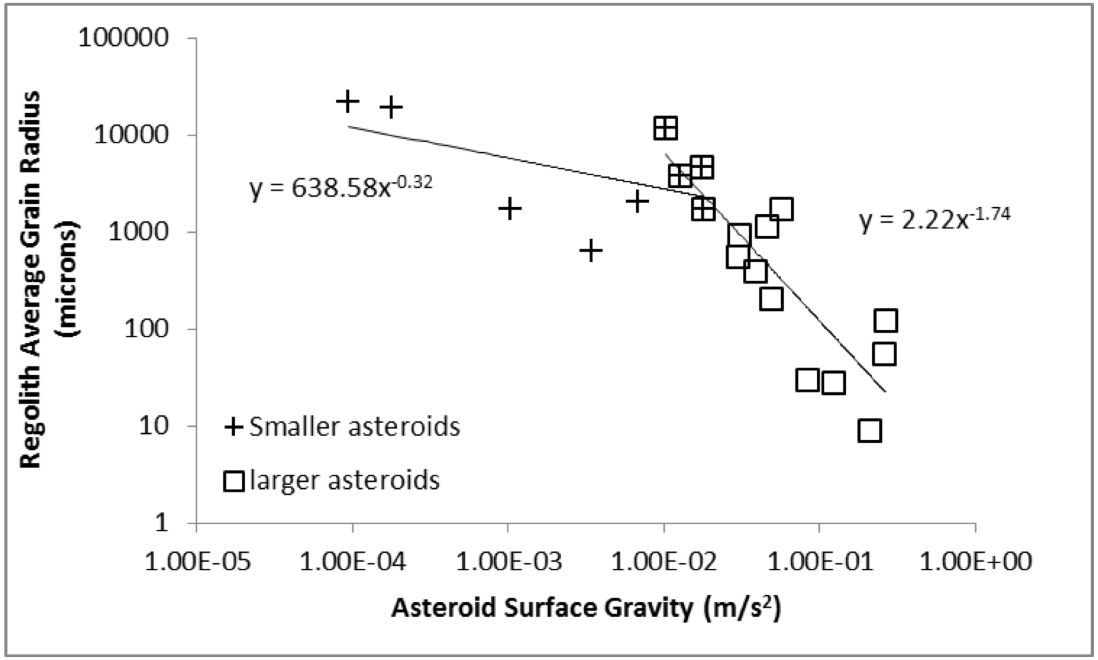
$$\delta F = \int_0^\infty \left| F_{\leq}^{S}(D) - F_{\leq}^{R}(D) \right| \mathrm{d}(\log_{10} D) \qquad \Phi_{PSD} = \max\left\{0, 1 - \frac{\delta F}{\log_{10} w}\right\}$$

What is the Particle Size Distribution for Asteroids?

- Inadequate data compared to the Moon
- We have to create a Reference *Model* in lieu of reference samples.
- Five sources of data:
  - Thermal inertia
  - Hayabusa returned sample
  - Hayabusa & NEAR images of surfaces
  - Disrupted asteroids
  - Meteorite breccias

Thermal Inertia Particle Sizing

- Gundlack and Blum (2013) developed relationship between thermal inertia and average particle size
- Data indicate smaller bodies have larger mean particle size
- Probably retention of disrupted fines due to larger gravity
- One simulant size will not fit all asteroids



Data replicated from Gundlack and Blum (*2013*) with added scaling laws for small and large asteroids

Hayabusa Sample & Images

- Combined Hayabusa data (Tsuchiyama et al, 2011) suggest *q* = -2.5
- *q* ≠ -3.5 suggests surface regolith was not in collisional equilibrium
  - or perhaps sampling method affected the distribution
- Surface may be denuded of fines by weathering
- Keihm et al (2012) found that 21 Lutetia has lower thermal inertia in the upper few centimeters, increasing with depth. Varying particle size?

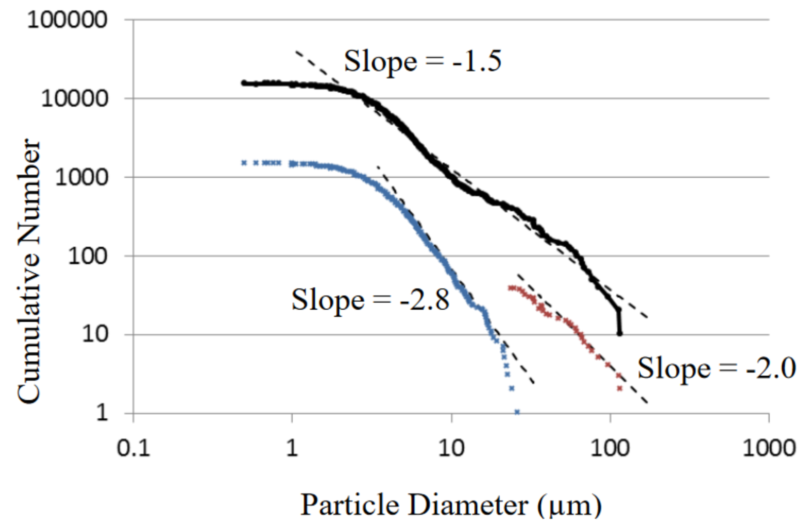


Figure 2. Cumulative size distribution of Itokawa particles. Blue (spatula) and red (tapping) and their fitting slopes are replicated from Tsuchiyama et al. (*2011*). Black is these two data sets combined, moved higher ×10 for clarity.

$$N_{\leq}^{\mathrm{Surf}}(D) = \begin{cases} 56{,}303.5\ D^{-1.5}, & 1\ \mu\mathrm{m} < D \leq 1.3\ \mathrm{m} \\ 145{,}016.5\ D^{-3.1}, & 1.3\ \mathrm{m} < D \leq 50\ \mathrm{m} \end{cases}$$

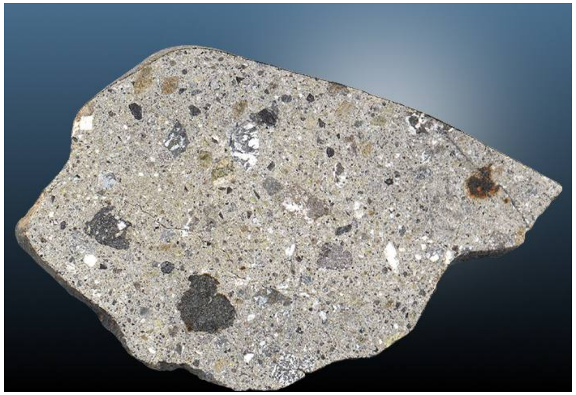
Disrupted Asteroids

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

Sources: Stevenson et al., 2012; Stevenson et al., 2012; Morena et al 2012; Jewitt et al, 2010; Snodgras et al, 2010; Kleyna et al, 2013, Hainaut et al., 2011, Jewitt et al., 2013; Snodgrass et al., 2010; Jewett et al., 2011; Ishiguro et al 2011.

- Observations agree with theory of Dohnanyi (1969) that predicts for particles in collisional equilibrium, q = -3.5.
- Max & Min particle sizes are controlled by impact dynamics and detection limit
  - not indicative of regolith mean particle size
- Compare: Kehoe et al (2015) found q = -3.1 for a zodiacal dust band from an older disrupted asteroid.

Meteorite Regolith Breccias



http://www.saharamet.com/meteorite/gallery/HED/

Meteorite	Apparent Exponent	Source
Yurtuk	1.28	Labotka and Papike
Frankfort	0.69	Labotka and Papike
ALHA 77302	0.88	Labotka and Papike
Pavloka	0.71	Labotka and Papike
Malvern	1.08	Labotka and Papike
Kapoeta	0.40	Pun et al.
Kapoeta Clast A	0.86	Pun et al.
Kapoeta Clast D	0.78	Pun et al.
Kapoeta	0.51	Fuhrman and Papike
Bununu	1.25	Fuhrman and Papike
Bholgati	0.54	Fuhrman and Papike
ALHA 76005	0.84	Fuhrman and Papike
Average	**0.82 ± 0.28**	

- HED regolith breccias are fossilized regolith of the parent body (Vesta?)
- Several have counted particles in 3 ranges:
  - N_1 in 20-200 microns
  - N_2 in 200-2000 microns
  - N_3 >2000 microns
- Calculate "apparent exponent"
  - $q_{eff} = 1 - \mathrm{Log}_{10}(N_2/N_1)$
- Results: regolith breccia texture does not represent collisional equilibrium
- Was regolith of Vesta not in collisional equilibrium?
- Or did brecciation change the particle sizing?

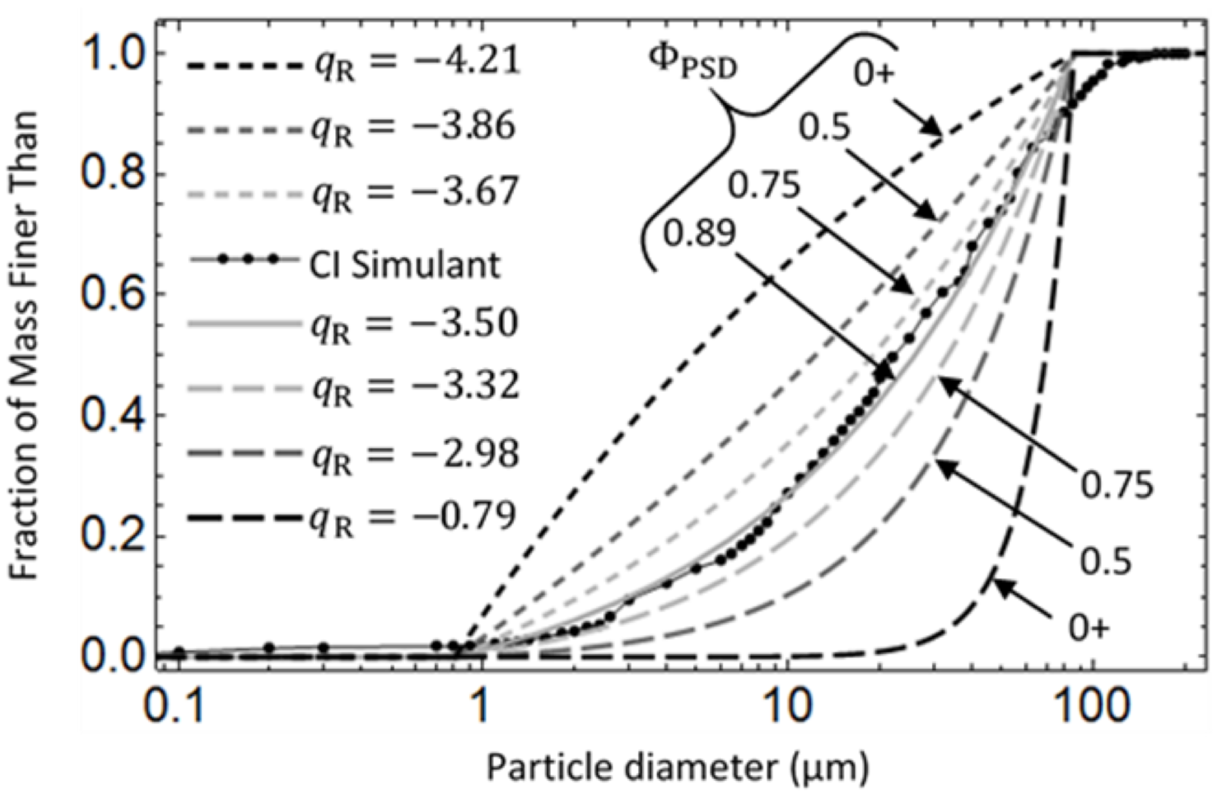
Reference Model for Asteroids

- We can (with fair confidence) specify the power law index for both surface deposits and bulk deposits

$$n_{\text{Ref}}(D) = \begin{cases} (1/c_1)\, D^{-2.5}, & D_{\text{Min}}^{\text{Surface}} \geq D \geq D_{\text{Max}}^{\text{Surface}}, \quad \text{for surface deposits} \\ (1/c_2)\, D^{-3.5}, & D_{\text{Min}}^{\text{Bulk}} \geq D \geq D_{\text{Max}}^{\text{Bulk}}, \quad \text{for bulk regolith} \end{cases}$$

- We cannot specify minimum and maximum particle sizes in the regolith
- In measuring FoM of a simulant, you can use the min and max particle size *of the simulant,* or use values that give the simulant the best FoM score.

Calculating FoM for Particle Size Distribution



SUMMARY

Summary of 8 Figures of Merit

Figure of Merit	Reference Sample or Model	Calculated FoM
Mineralogical	Orgueil analyzed by Bland et al. (2004)	0.83*
Elemental	Stoichiometry from the mineral analysis of Orgueil	0.94*
Mineral Grain Density	Measurements of Orgueil by Consolmagno and Britt (1998)	0.75
Cobble Bulk Density	Measurements of Orgueil by Consolmagno and Britt (1998)	0.72
Magnetic Susceptibility	Multiple measurements of Orgueil	0.96
Cobble Strength	Model based on micro-indenter measurements of tensile strength of Orgueil by Tsuchiyama et al. (2008) scaled-up to compressive strength of larger fragments	0.77
Volatile Release	Orgueil analyzed by King et al. (2015)	0.53
Particle Sizing	Model based on Hayabusa sample return, boulder counting on Itokawa, and disrupted asteroids	0.55 – 0.89** (bulk) 0 – 0.57** (surficial)

Conclusions

- NASA's Figure of Merit system for lunar simulants has been revised and extended for asteroid simulants
- The system is complicated.
- It can be written into a web tool enabling users to easily and rapidly compare simulants to various reference materials
- We recommend the community adopt and continue adapting this system to prevent the problems that were seen earlier in lunar testing.

	Property	Type	Equation	w
Φ_{M}	Mineralogical	Vector (pseudo-) inner product in ℓ_1	$\Phi_{\mathrm{M}}(\vec{S}_{\mathrm{M}}, \vec{R}_{\mathrm{M}}) = \left\Vert \vec{S}_{\mathrm{M}} \cap \vec{R}_{\mathrm{M}} \right\Vert_1 = \sum_{i=1}^{N_{\mathrm{M}}} \min(s_i, r_i)$	--
Φ_{E}	Elemental	Vector (pseudo-) inner product in ℓ_1	$\Phi_{\mathrm{E}}(\vec{R}_{\mathrm{E}}, \vec{S}_{\mathrm{E}}) = \left\Vert \vec{S}_{\mathrm{E}} \cap \vec{R}_{\mathrm{E}} \right\Vert_1 = \sum_{i=1}^{N_{\mathrm{E}}} \min(v_i, w_i)$	--
Φ_{D}	Average Grain Density (cobbles and regolith)	Linear scalar difference	$\Phi_{\mathrm{D}} = \max\left\{0, 1 - \frac{1}{w} \frac{\left\vert \rho_{\mathrm{g}}^{\mathrm{S}} - \rho_{\mathrm{g}}^{\mathrm{R}} \right\vert}{\rho_{\mathrm{g}}^{R}}\right\}$	0.5
Φ_{BD}	Cobble Bulk Density	Linear scalar difference	$\Phi_{\mathrm{BD}} = \max\left\{0, 1 - \frac{1}{w} \frac{\left\vert \rho_{\mathrm{bulk}}^{\mathrm{S}} - \rho_{\mathrm{bulk}}^{\mathrm{R}} \right\vert}{\rho_{\mathrm{bulk}}^{R}}\right\}$	0.5
Φ_{CS}	Cobble strength	Logarithmic scalar difference	$\Phi_{\mathrm{CS}} = \max\left\{0, 1 - \frac{\left\vert \log_{10} U^{\mathrm{S}} - \log_{10} U^{\mathrm{R}} \right\vert}{\log_{10} w}\right\}$	5
Φ_{MS}	Magnetic Susceptibility	Logarithmic scalar difference	$\Phi_{\mathrm{MS}} = \max\left\{0, 1 - \frac{\left\vert \log_{10} \chi^{\mathrm{S}} - \log_{10} \chi^{\mathrm{R}} \right\vert}{\log_{10} w}\right\}$	5
Φ_{VR}	Volatile Release	Linear ℓ_1-norm of difference function	$\Phi_{\mathrm{VR}} = \max\left\{0, 1 - \frac{1}{w} \frac{\int_{T_{\min}}^{T_{\max}} \vert v_{\mathrm{S}} - v_{\mathrm{R}} \vert \, \mathrm{d}T}{\int_{T_{\min}}^{T_{\max}} \vert v_{\mathrm{R}} \vert \, \mathrm{d}T}\right\}$	1
Φ_{PSD}	Particle Size Distribution	Logarithmic ℓ_1-norm of difference function	$\Phi_{\mathrm{PSD}} = \max\left\{0, 1 - \frac{\int_{\log D_0}^{\infty} \left\vert F_{\leq}^{\mathrm{S}}(D) - F_{\leq}^{\mathrm{R}}(D) \right\vert \, \mathrm{d}(\log D)}{\log_{10} w}\right\}$	3.5