Figure of Merit Characteristics Compared to Engineering Parameters

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Introduction

Current NASA lunar architecture calls for permanent human habitation of the moon by the year 2020. Due to the expense of delivering materials into orbit, technologies are being developed to use lunar regolith for building and as a material resource for fabrication, oxygen production, and other needs. Additionally, constant exposure to the finest size fraction of lunar regolith may present hazards to human health. Towards developing these technologies and mitigating hazards, lunar regolith simulants are becoming an increasingly important part of the development paradigm.

2005 Regolith simulant workshop

In January of 2005, Marshall Space Flight Center (MSFC) hosted a workshop in Huntsville, Alabama to discuss the future development of lunar regolith simulants. This meeting brought together geoscientists – including some major figures in lunar geology, project managers, engineers, and simulant users from NASA centers, academia, and private enterprise. In addition to two days of presentations (content available at http://est.msfc.nasa.gov/workshops/lrsm2005_program.html), sessions were held to identify characteristics necessary for a lunar regolith simulant to sufficiently serve the community. Regolith characteristics were discussed and votes were taken with regard to perceived importance. Rankings of these properties were published in a technical paper by Sibille et al. (2006) following the 2005 workshop.

Development of Figures of Merit (FoM)

Between 2005 and 2007, the lunar regolith simulant project advanced considerably. Much of the progress and development is evident in presentations of the October 2007 MSFC-hosted Huntsville workshop (http://isru.msfc.nasa.gov/2007wksp_docs.html). Part of the evolution was the establishment of the Figure of Merit (FoM) mathematics and algorithm (Rickman, et al, 2007; and MSFC-RQMT-3503 (DRAFT)) for formal, quantitative comparison of two particulate materials composed of geologic components. Although the normally the comparison will be between a particular sample of lunar regolith and a simulant, the FoM can also be used to compare two simulants or two regolith samples.

Explanation of the 2005 workshop rankings with the FoM

The primary motivation for this document is to define the relationship between the four Figure of Merit measurements and other characteristics of interest. For the most part, it is shown, the characteristics of interest from the 2005 conference are either directly contained within one of the four attributes measured for and evaluated by the FoM, or they are derivative characteristics resulting from one or a combination of the FoM attributes. In cases where the ranked characteristics from the 2005 workshop are not measurable, technically undefined, or not addressed by the FoM, this information is presented as well along with a brief explanation.

FoM

Objective of FoM

The FoM was designed as a practical and efficient way to characterize and compare materials. Towards this end the parameters for evaluation are chosen to be -

- definable: many characteristics of materials are not rigorously defined – this is true even of some important physical characteristics like "surface activation";
- measurable: parameters were chosen that can be measured economically, in a timely fashion, and with results reproducible across laboratories;
- useful: for simplicity of design, parameters were chosen that correlate to properties important to the functioning of simulant under expected conditions;
- primary versus derivative: this concept recurs through out the FoM logic; some characteristics are inherent to a material, like the composition of its constituents, be they minerals or glass – other properties like the behavior of a material during heating are derivative of the composition, all else being equal.

These are positive attributes desirable in any standard.

Expressed in the negative, if something can not be rigorously defined and measured reproducibly by multiple people it has little value in a standard. If it can not be practically known, a problem common with lunar materials for a host of reasons, it is not of function utility within a standard. If a variable can not be realistically be measured in a way suitable for controlling the manufacture and the use of simulants it has little place in a standard. If a parameter does not discriminate between materials it has limited function to a quantitative standard.

Parameters

The FoM requires four types of measurements from both the reference material and the simulant: particle type, particle size, particle shape, and density. These four material attributes were chosen to comply with the above objectives and because they are measurable quantities from which almost all of the 31 characteristics ranked during the 2005 conference are derived. They also are functionally useful to anyone seeking materials to make simulant, to those trying to manufacture simulant and to those trying to use the simulant.

For a formal definition of the four characteristics please see MSFC-RQMT-3503 (DRAFT).

Particle type/Composition

Composition describes attributes of a particle that exist without regard to size or shape. Here, we use the term *particle* to mean a piece of solid matter mechanically separable from others, such as by use of a sieve. The 2005 report uses the terms "grain" for several basic concepts. This is common practice for geologists, who by training and experience understand the meaning by context. Because the majority of simulant users and developers are not geologists, the simulant development project explicitly decided to restrict "grain" to mean a discrete subset of a particle. All particles in lunar regolith or simulant will be comprised of glass and/or mineral "grains", but particles may be amalgam of grains that result in lithic fragments (rock particles) or agglutinates.

Therefore, the first order of classification of constituents includes mineral grains, glass grains, lithic fragments, and agglutinates. Measuring proportions of particle types by volume is known in geologic science as a "modal analysis", and is usually reported in modal % by each constituent. Although it is not required by the Figure of Merit, it is ideal that modal analyses be obtained for a material in several different size fractions. This is because the percentages of constituents of any bulk material will tend to vary by size due to differential susceptibility to grinding and crushing. Modal analyses for lunar highlands regolith have been published (e.g., Houck,1982). These data serve as the basis for the regolith simulant team's reference material in the FoM algorithm, but more precise data are being gathered to augment them.

Particle size distribution

For the Figure of Merit, particle size is measured on a particle by particle basis and reported as a distribution. The number of bins and the size of the bins are defined by the user, but a more precise FoM evaluation is rendered by an approximation to the lunar regolith dataset. These data can be found in, for instance The Lunar Soils Grain Size Catalog (Graf, 1993).

Particle shape distribution

Particle shape is a crucial parameter in determining many geotechnical properties such as abrasiveness and bulk shear strength. The Figure of Merit calls for measurement of shape on a particle by particle basis which is then reported as a distribution. Shape is described by two parameters – aspect ratio and sphericity. The specific algorithms for measuring these characteristics are being determined.

Density

Density as a Figure of Merit parameter refers to bulk density, and it is the only parameter that is not measured by the particle but as a bulk characteristic. The measurements that comprise the density FoM are minimum bulk density, maximum bulk density, and specific gravity. Measured as such, the bulk density FoM conveys information as to the specific gravity of the constituent particles and on the packing – or the bulk relationship of the particles to one another. It is the FoM property most easily affected by handling of the simulant.

Evaluation of Recommended Properties vs. FoM

Table 1 contains the ranked properties from the 2005 workshop. It should be noted that rigorous definitions of these properties were not provided, and neither were suggested measurement protocols or standards.

Category		Category Properties Listing	
		Regolith Property	Rank
Geomechanical (mechanical strength properties)		Compressive strength	10
Total number of ranked properties	11	Coefficient of friction	12
Number of properties in top 10	1	Shear strength	18
		Hardness	23
		Rheology	24
		Angle of repose	25
		Tensile strength	27
		Fracture behavior	28
		Impact resistance	32
Physical		Particle density	3
Total Number of Ranked Properties	7	Bulk density	5
Number of Properties in Top 10	2	Porosity	13
		Thermal properties	20
		Surface area	21
		Friability	22
		Permeability	26
Grain Specific		Grain size	1
Total Number of Ranked Properties	6	Grain size distribution	2
Number of Properties in Top 10	4	Grain shape	7
		Magnetic grain properties	9
		Grain shape distribution	16
		Electrostatic charging	17
Chemical		Glass composition	4
Total Number of Ranked Properties	6	Bulk chemistry	8
Number of Properties in Top 10	4	Reactivity as volatile/soluble minerals	14
		Surface reactivity (including damage)	29
Mineralogical		Mineralogical composition as function of grain size	6
Total Number of Ranked Properties	4	Modal mineralogical composition	11
Number of Properties in Top 10	2	Soil texture	30
Multicategory		Implanted solar particles	15
Total Number of Ranked Properties	2	Agglutinates with nanophase Fe	31
Number of Properties in Top 10	0		

Table 1 Properties from the 2005 Lunar Simulant Workshop, from table 2 in Sibille et al. (2005).

The 2005 report uses the terms "grain" for several basic concepts. This is common practice for geologists, who by training and experience understand the meaning by context. Because the majority of simulant users and developers are not geologists, the simulant development project has subsequently decided to explicitly restrict “grain” to mean a discrete subset of a particle. In concept, a particle is a physically isolatable mass not chemically bonded to anything else. The grain commonly is a crystal of a mineral, but it can also be a piece of glass.

See Table 2 for relations of properties to the FoM. For each parameter that is not explicitly a part of the FoM standard, comments are provided. In most cases the comments indicate the basic science explaining how the property is a derivative property. Also, where there are limitations to the assumptions or assertions made, some consideration of the limitations is given.

Geomechanical (mechanical strength properties)

Compressive strength

This is a derivative property. It is a function of the particles’ composition, their size, shape and how they are packed together. To the limit the FoM parameters can be measured in both the simulant and the lunar material this property is tightly constrained by the FoM.

Table 2: Properties from 2005 workshop correlated to FoM properties by which they are directly addressed of from which they derive.

Category Properties Listing **Regolith Property**	**Particle type**	**Paricle size distribution**	**Particle shape distribution**	**Density**	**Not addressed or undefined**
Compressive Strength	■	■	■	■	
Coefficient of friction	■	■	■	■	
Shear strength	■	■	■	■	
Hardness	■				
Rheology		■	■	■	
Angle of repose		■	■	■	
Tensile strength					X
Fracture behavior	■				
Impact resistance	■				
Particle density	■				
Bulk density				■	
Porosity		■	■	■	
Thermal properties	■	■	▒	■	
Surface area		■	■		

Friability					
Permeability		▦	▦	▦	
Grain size		■			
Grain size distribution		■			
Grain shape			■		
Grain shape disribution			■		
Magnetic grain properties	▦	▦			
Electrostatic charging	░	░	░	░	
Glass composition	■				
Bulk chemistry	▦				
Reactivity as volatile/soluble minerals	▦	▦	▦	▦	X
Surface reactivity	▦	▦	▦	▦	X
Mineralogical composition as function of grain size	■				
Modal mineralogical composition	■				
Soil texture		▦	▦	▦	X
Implanted solar particles					X
Agglutinates with nanophase Fe	■				

■	Property directly addressed by FoM
▦	Property derivative of FoM property
░	Property partially dependent on environment

Coefficient of friction

This is a derivative property. It is a function of the particles' composition, size, shape, and packing. To the limit the FoM parameters can be measured in both the simulant and the lunar material this property is tightly constrained by the FoM.

Shear strength

This is a derivative property. It is a function of the particles composition, their size, shape and how they are packed together. To the limit the FoM parameters can be measured in both the simulant and the lunar material this property is tightly constrained by the FoM.

Hardness

'Hardness' as a geomechanical property is ambiguous or undefined at best. In the 2005 workshop report the context of usage is always with respect to a single particle. In the report the usage is also with either the explicit statement or the assumption of mineral hardness as used by geologists. Assuming this is the intention of the term the FoM Particle Type very tightly constrains this property. The limitation is the mechanical strength of lithic fragments and shattered particles. For this small minority of particles the basic concept breaks down. In engineering applications terms such as abrasiveness are substituted.

Rheology

Definition – the branch of physics that deals with the deformation and flow of matter, esp. the non-Newtonian flow of liquids and the plastic flow of solids.

As used in the 2005 workshop report, "The rheological behavior (flow properties) of the regolith is a key property of the bulk material during excavation."

The flow properties of a material are largely determined by the particle size and shape distribution and the bulk density.

Angle of repose

The rheological behavior (flow properties) of the regolith is a key property of the bulk material during excavation. As an example, it manifests itself in the angle of repose of a regolith slope forming a trench or an erected berm. See Rheology, above.

Tensile strength

The varying types of tensile strength describe a material's reaction to stress and are defined as the maximum stress before rupture (breaking strength) or deformation (yield strength). The tensile strength of an individual particle is entirely constrained by the composition of the particle, although the properties may not have been adequately measured for some composite particles like breccias and agglutinates. Tensile strength of the bulk material is less well defined, but it should be derivative of all of the four FoM characteristics.

Fracture behavior

Fracture behavior of particles is driven by the particle type, specifically the hardness, cleavage and fracture properties inherent in mineral and glass. These are addressed by the FoM, and to some extent by particle shape. Whether and how particles fracture in a bulk material as a response to stress is dependent on their size and packing as well.

Impact resistance

Impact resistance should be akin to fracture behavior (4.2.8).

Physical

Particle density

If the particle type is known, this can be directly computed to high or very high precision. The limitation is for particles with large amounts of internal voids, such as agglutinates and to lesser extent shattered particles. The significance of this error for a bulk sample is estimated to be much less than 1%. For individual particles it is estimated to be as high as 20%. These values can be quantified by appropriate analyses, as proposed in the Data Acquisition Plan.

Bulk density

This is an explicit part of the FoM standard. Note however, it is not rigorously defined in the 2005 recommendations.

Porosity

Porosity is a function of the particle type (due to vugs and voids in particles) shape and size distribution, and bulk density. It may not be uniquely constrained by these characteristics.

Thermal properties

Thermal properties are derivative of the particle type, size and shape distribution, and bulk density. Particles will have distinct conductive/insulating properties and the contact relationships between them will depend on size, shape, and bulk density.

Surface area

Surface area is a function of particle size and shape distribution, and the surface area exposed in a given volume of material will also be determined by its bulk density. Surface area is uniquely constrained by these parameters, but effective surface area defined as surface area available for contact is more largely dependent on the type of packing which may not be uniquely described by the bulk density parameter.

Friability

Most simulants are expected to be unconsolidated on the bulk scale and thus friability, defined as the tendency to reduce to finer particles under stress, is not applicable. Individual particles in a simulant or regolith such as breccias may be friable. Although friability and other measurements of mechanical strength are important considerations in simulant production, the properties of lunar regolith have not been measured adequately enough to simulate.

Permeability

Permeability is a function of the particle shape and size distribution and bulk density. It may not be uniquely constrained by these characteristics.

Grain Specific

Size and shape are not defined by the 2005 workshop report. These concepts can only be given physical meaning by defining a specific method of measurement. Many of the measurement methods have physical meaning or are only applied to assemblies of particles.

Grain size

This is an explicit part of the FoM standard.

Grain size distribution

This is an explicit part of the FoM standard.

Grain shape

This is an explicit part of the FoM standard.

Magnetic grain properties

Magnetic properties derive from the mineralogy, grain or particle size, and environmental history of the particle. For example heating above a material specific temperature will cause a radical change in magnetic response. Subsequent cooling will change it yet again. In lunar materials particle composition should determine most of the magnetism of the bulk material, but this is complicated by the presence of nanophase Fe (nFe^0) in the lunar regolith. At this time nFe^0 is normally considered as a distinct solid phase independent of the commonly present iron (Fe^0) derived from meteoritic sources. nFe^0 is present in the agglutinates and as vapor-deposited nano-scale rimes on particles. As of now, the nFe^0 in the agglutinates can only be partially reproduced and that is at significant cost. The rimes can not be reproduced.

The FoM incorporates the mineral phase native iron (Fe^0). This was done to address both the meteoritic derived iron and the nFe^0 . The FoM also explicitly incorporates the particle type “agglutinate”. It is concluded that when fully implemented these two measures, with the other FoM characteristics, will reasonably cover the performance of lunar and simulants. This is almost certainly true for first order and probably most second order measurement. It is acknowledged that this may not be the case for very high quality measurements due to the role of particle history. As there is so little applicable information of any kind on this topic for actual lunar material, inclusion of such a parameter in the current FoM would violate basic characteristics of a standard, being neither measurable or known.

Grain shape distribution

This is an explicit part of the FoM standard.

Electrostatic charging

This is not part of the FoM standard. There is little data on the parameter for lunar material. It is almost certainly dominated by the composition and size of the particles, which is addressed by the particle type and size FoM. The limitation on this is the effect of the vapor-deposited rims.

Chemical

Glass composition

Glass composition is important to many applications like ISRU and fabrication. Theoretically, the particle type FoM measures abundance and composition of particles. The diverse populations of glass compositions in lunar regolith pose a unique problem for evaluation. In the first FoM software release, only glass abundance is included in the algorithm, though there are entry spaces for subclasses of glass. This allows the user to define populations of glass (e.g., basaltic glass, Ti-rich basaltic glass, etc.) in the reference and simulant. Future revisions to the FoM software will include a routine to compare the chemical composition of glass in the materials, as well as the abundance.

Bulk chemistry

This is an implicit part of the FoM standard. If one knows the composition of the particles one knows the bulk chemistry. The limitation to this is a question of precision. The standardized list of minerals does not cover all possible minerals. Nor does it attempt to specify glass composition other than to restrict it by normative mineralogy. The minor element (<1 wt.%) and trace element (<0.1 wt.%) chemistry of a material is less well determined by particle type composition, except for cases like P, which is specifically addressed by reporting the modal % of phosphates – the only minerals in which it's likely to occur.

Reactivity as volatile/soluble minerals

Although the meaning of this entry is not entirely clear in the 2005 workshop document, it seems to refer to volatile (e.g., OH, H_2O, CO_2)-bearing materials and halogen (F, Cl, Br, I)-bearing materials.

OH, H_2O, CO_2-bearing materials

For the former case: their presence in a simulant invokes a penalty to the composition FoM because correlative materials do not occur in lunar regolith. Furthermore, in revision 1 of the FoM software, these volatile-bearing minerals will populate their own subclass under the "non-lunar minerals" heading, and their presence will be weighted more than other non-lunar minerals due to their adverse affects on many ISRU processes.

Halogen-bearing materials

For the latter case: the primary F- and Cl-bearing mineral in lunar regolith is the phosphate apatite. There is an entry for fluoroapatite on the FoM composition sheet, and so its presence, or lack thereof, will be assessed.

Surface reactivity (including damage)

Surface reactivity is dependent on particle type, for reasons of chemistry, and on surface area (see 4.3.5). It is also dependent on the "activation" of a particle surface – a variable condition determined by particle lattice damage, lack or presence of adsorbates, and other characteristics. No general, measurable parameter correlates to this condition. Furthermore, it would seem to be a dynamic condition that would be difficult to impart to a bulk material by the manufacturer.

Mineralogical

Mineralogical composition as function of grain size

This is an explicit part of the FoM standard.

Modal mineralogical composition

This is an explicit part of the FoM standard.

Soil texture

This is not defined and has many, many meanings. Some of the possible meanings are directly related to size and shape distribution and to material density.

Multi-category

Implanted solar particles

This is not addressed by the FoM as of this date. It is not considered practical or useful to add during simulant production. Reproduction of the process or result would likely be very expensive and it seems best for treatment to replicate this property be carried out by the investigator. This may change in the future.

Agglutinates with nanophase Fe (nFe$^{0)}$

The presence of nanophase Fe in the agglutinates can be addressed by the particle type FoM. In version 1 of the software data on the distributions of agglutinates are required. A subclass could be added of those agglutinates containing nanophase Fe after this property is defined in the requirements document.

Conclusion

The Figure of Merit is considered to be a work in progress, both conceptually and in terms of algorithm and software development. It provides a reasonable and practical means to compare materials by addressing fundamental, inherent, measurable characteristics.

References

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