THE NEED FOR LUNAR SOIL SIMULANTS FOR ISRU STUDIES

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INTRODUCTION: The establishment of a base of operations on the Moon in preparation for and implementation of further exploration of the Solar System looms large upon the horizon. Paramount in these endeavors is the need to learn to "live off the land" on the Moon [1]. This will involve the "In-Situ Resource Utilization" (ISRU) of the materials on the lunar surface for a myriad of uses. The surface mobility (rovers), scientific instrument, and EVA (extra vehicular activity) communities also must address the lunar materials as well. The various engineering and material science studies that are necessary for these endeavors will mostly address the lunar regolith (crushed rock) and soil (<1 cm of regolith) for their starting materials on the Moon and there is need of these materials for such pursuits. However, the Apollo lunar samples are a national treasure that must be protected from unnecessary usage. There is an obvious and important need for simulants of the lunar regolith/soil with which these investigations can meaningfully proceed [2,3].

It is obvious that many factors must be considered in making lunar simulants for various ISRU projects. This subject is of major importance as we move into the near-future endeavors associated with a return to the Moon. Herein, we address the detailed geologic specifics of lunar soil and list many of the geotechnical properties [4] that should be considered before we produce simulants for definitive study purposes. It is proposed that a *Lunar Soil Simulant Consortium* certify, standardize, manufacture, and otherwise regulate the use of simulants for ISRU purposes and other studies in order to have simulant materials with which to make comparisons between investigations more valid and consistent and meaningful [2].

UNIQUENESS: The formation of the lunar regolith is due to space weathering, a combination of factors affecting materials in the deep vacuum and low temperature of space [5]. However, whereas water is the dominant weathering process on Earth, the process of micrometeorite(<1 mm) impacts is the dominant factor on the Moon, a direct result of the lack of an atmosphere. Although of small mass, these particles possess huge amounts of kinetic energy, impinging on the lunar surface with velocities up to 100,000 km/hr. Much of the impacting energy goes into breaking and crushing of fragments into smaller pieces, however, many impacts completely melt the soil, on scales of millimeters. The melted soil incorporates soil fragments and quenches to glass. Thereby, these aggregates of minerals, rocks, and prior-existing glasses are welded together (i.e., cemented) by the melt glass to form "agglutinates" [6]. The glass in these fragile agglutinates further becomes broken into smaller pieces making for ever-increasing amounts of glass to the soils as they mature [7]. In fact, the most abundant component of lunar soils consists of these glassy agglutinates and their crushed pieces, present as sharp, abrasive, interlocking, fragile, glass shards and fragments. Portions of these silicate impact melts also vaporize, only to condense upon the surfaces of all soil grains as glassy rinds elemental Fe^0 grains [8].

Impingement of cosmic, galactic, and solar-wind particles also perform minor weathering, largely by sputtering, but many of these particles remain imbedded in the outer portions of all lunar soil grains, mainly as hydrogen and helium [9]. This highly reducing, solar-wind hydrogen participates in the impact melts of the soil, as well as with the vaporized chemistry, to produce *a unique feature of the lunar soil*, the quenched glass containing a *plethora* *of nano-sized Fe^0 grains (4-33 nm),* with the soil containing 10X more elemental Fe^0 than the rocks from which it was derived [10].

This nanophase Fe^0, in its glass host, is most abundant in the finest portions (<50 µm) portion of the soil, the "dust" [5], where it imparts unique properties to the soil – namely, 1) greatly increased magnetic susceptibility due to the ferromagnetic Fe^0, and 2) greatly enhanced coupling to microwave energy, which facilitates exceedingly rapid heating and melting of the lunar soil [11]. It is this same abundant "dust" at <50 µm that contributed to numerous problems for the astronauts during their EVAs on the Moon [12]. It is the mainly the presence of these huge quantities of glass that contributes to the unusual engineering properties of lunar soil [4], properties that are difficult to reproduce with simulants.

NEEDS: Studies for lunar ISRU include: Facilities construction, regolith digging and moving, trafficability (e.g., roads, landing pads), microwave processing, conventional heat sintering, oxygen production, dust abatement, mineral beneficiation, solar-wind gas release, cement manufacture, radiation protection, et cetera. The chart below summarizes some of the needs for lunar stimulant versus the differences between some of the simulants previously produced, albeit no longer available [2]. In the chart, the number of X's is related to the degree to which a stimulant applies to the specific topic.

During the recent Space Resources Rountable VI meeting at Colorado School of Mines, the audience largely of BAA industrial and university proposers were polled as to how much lunar soil stimulant they expect to need in the near future. Seven (7) indicated they would need >10 tons, and two (2) indicated that they would need >100 tons. I personally know of one company that expects to use 600 tons. From this somewhat limited sampling, it is apparent that there will be a near-term need for a quantity that could approach 1000 tons of lunar soil simulant.

"One Simulant Does Not Fit All Needs"

SIMULANTS ARE NEEDED FOR STUDIES OF:

	Chemistry	Geotech/Engr	Simulant
Facilities Construction	X	XX	JSC-2 (= old JSC-1)
Regolith Digging and Movin		XX	JSC-2
Trafficability (e.g., Roads)		XX	JSC-2
Microwave Processing	XX	X	NP-1+JSC-2+MLS-2
Conventional Heat Treatment	X	X	JSC-2+MLS-2
Oxygen Production	X	X	JSC-2+MLS-1+MLS-2
Dust Abatement	X	X	NP-1+JSC-2
Mineral Beneficiation	X	X	???
Solar-Wind Gas Release	X	X	JSC-2+Ion Implant
Cement Manufacture	XX		MLS-1+MLS-2
Radiation Protection	X	X	JSC-2+MLS-1+MLS-2

Mare Soil:	JSC-2	= JSC-1 in chemistry + Geotech Prop.
	MLS-1	= Chemistry only of Apollo 11 soil (no glass)
Highland Soil:	MLS-2	= Anorthosite = Chemistry only
Magnetic Soil:	NP-1	= Magnetic properties only

A Lunar & Martian Soil Simulant Workshop will be convened at MSFC, in collaboration with JSC, in January 2005 to discuss further the needs of the community and to address the manufacture and distribution of such simulants. The persons listed below in the Lunar Soil Simulant Consortium will play major parts in this endeavor.

PRODUCTION: A workshop [13] was held in 1991 to evaluate the status of simulated lunar material and to make recommendations on future requirements and production of such material. This resulted in the production of a mare basalt simulant, JSC-1, which was used by many groups. However, since the Apollo days, there have been several small lunar ISRU projects, many funded through SBIR contracts. Several lunar soil simulants were produced during this period; however, because they were not standardized, data from experiments performed with them were not necessarily equivalent to test results performed on other simulants. An attempt was made to focus on the production and dispersement of two standardized simulants: MLS-1, a crushed hi-Ti basalt from Minnesota that has a chemistry similar to Apollo 11 soil 10084, but not the geotechnical properties [14]; and JSC-1, produced through JSC in 1993 and made from a volcanic rock from near Flagstaff, AZ, which had lots of glass and good geotechnical properties, but not the best of lunar soil compositions [15]. However, these simulants have long ago been depleted. Hence, the need for a new plan for lunar soil stimulant production.

It was a general consensus at the Space Roundtable meeting that there should be three (3) 'root' simulants produced: 1) a typical mare soil; 2) a highland soil; and 3) a South Pole soil stimulant. The basic properties should be similar for all simulants: grain size, grain size distribution, a mixture of lithic fragments, mineral fragments, and glassy particles, a chemistry judged to be appropriate. The concept of a standardized simulant should be followed by the lunar ISRU community, in which large quantities (more than 100 tons) of simulant is produced in a manner that homogenizes it so that all subsamples are equivalent. From this root simulant it would then be possible to produce other more specialized simulants, for example, by implanting solar wind, by adding ice in various proportions, or by adding specific components such as metallic iron, carbon, organics, halogens, etc. to more closely simulate exceptional properties of lunar regolith needed for specific kinds of tests and experiments. In all cases, the specialized simulant branches should be traceable to the root simulant.

It is proposed that the root simulants be collected at a single locality and characterized by a science and engineering team [2-3]. New security restrictions make it difficult for JSC to be the collection and distribution site; it will be necessary to perform this service elsewhere. While JSC-1 was distributed at no cost to the customers other than shipping, in this new era of full-cost accounting, the simulant must be paid for by the customers.

MANAGEMENT: We encourage NASA to sanction and establish a Lunar Soil Simulant Consortium to be responsible for the production, standardization, testing, certification, and distribution of the simulants. Drs. Dave McKay [JSC], David Carrier [Lunar Geotechnical Inst., FL], and Larry Taylor [Planetary Geosciences Inst., U of TN] are 'lunatics' of the first order, experts in the physical, chemical, and geotechnical properties of lunar regolith, and the best qualified for this endeavor. Drs. James Carter [U of TX, Dallas], and Paul Weiblen [U of MN] have extensive experience in the production of previous two lunar simulants (JSC-1 and MLS-1, resp.). Larry Taylor has volunteered to be the Leader of this consortium.

Geotechnical Soil Properties for Consideration in Lunar Soil Simulants [4]:
Particle Size Distribution; Particle Shapes; Specific Gravity; Bulk Density; Soil Porosity; Compressibility; Shear Strength; Permeability; Diffusivity; Bearing Capacity; Ultimate Slope Stability; Trafficability; Electrical Conductivity; Dielectric Permittivity; Magnetic Susceptability;

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