Planetary and Space Science 126 (2016) 1–7

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Evaluations of lunar regolith simulants

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ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form
14 April 2016
Accepted 18 April 2016
Available online 20 April 2016

ABSTRACT

Apollo lunar regolith samples are not available in quantity for engineering studies with *In-Situ* Resource Utilization (ISRU). Therefore, with expectation of a return to the Moon, dozens of regolith (soil) simulants have been developed, to some extent a result of inefficient distribution of NASA-sanctioned simulants. In this paper, we review many of these simulants, with evaluations of their short-comings. In 2010, the NAC–PSS committee instructed the Lunar Exploration Advisory Group (LEAG) and CAPTEM (the NASA committee recommending on the appropriations of Apollo samples) to report on the status of lunar regolith simulants. This report is reviewed here-in, along with a list of the plethora of lunar regolith simulants and references. In addition, and importantly, a special, unique Apollo 17 soil sample (70050) discussed, which has many of the properties sought for ISRU studies, should be available in reasonable amounts for ISRU studies.

1. Introduction

The production for lunar regolith simulants has only partially satisfied the needs of the In-Situ Resource Utilization engineering community. There is still a need for Apollo soil samples for certain ISRU endeavors. These are two of the conclusions of the LEAG-CAPTEM-SWG report (Lunar Exploration Advisory Group – Center for Analysis and Planning Team for Extraterrestrial Materials – Simulant Working Group – 2010, from a study requested by NASA Advisory Council–Planetary Sciences Sub-Committee (NAC–PSS)). Some significant conclusions are in the products of this LEAG-SWG Report, and are expanded upon in this paper.

Although lunar simulants are supposed to be effective copycats of lunar soils (McKay et al., 1994), with similar chemical compositions, mineralogy, particle size distributions, and engineering properties as lunar soils, they are extremely difficult to make in bulk and with uniform properties. The products have not been satisfactory, in many cases. A simulant made for one purpose may be entirely unsatisfactory for another. For example, during Apollo time, the best regolith simulant with proper engineering properties for *"research on drilling into lunar soil"* was a mixture of *"League City sand and kaolinite,"* a local sand and clay (David Carrier, pers. comm.). But, this soil simulant was totally wrong with regards to lunar mineralogy, composition, particle size distribution, et cetera. The misuse of lunar regolith simulants appears to be due to a lack of integration of lunar science with the engineering needs. Examples of in-sufficiently prepared soil simulants are presented, especially for the production of some expensive simulants by Taylor and Liu (2010).

We are always told that the Apollo lunar rocks and soils are a national treasure and cannot be used in any real quantity for ISRU studies. However, the author, a member of the "backroom" at JSC during the Apollo 17 Mission remembered a strange sample that Astronaut Jack Schmitt bagged, and which was curated, but thence forgotten. This Apollo 17 soil lacks provenance, because it was part of the debris thrown up (broken fender) onto the Buddy Secondary Life Support System (BSLSS) of the Lunar Rover Vehicle (LRV) during the third EVA, and bagged with the name BSLSS Bag sample. It is a mixture of soil particles from all over the EVA traverse, particularly of the third. This sample number **70050** soil is over 2.2 kg and can be used for many engineering studies, since it lacks requisite provenance for most scientific uses. The chemistry and mineralogy of this soil are described herein.

2. History of lunar soil simulants

It is well known, yet not fully appreciated, that "one-of-a-kind lunar simulant does not fit all needs". Understanding the history of the development of lunar simulants should give us some insight as to the present-day problems that still exist. In order to make a simulant that duplicated the lunar soil geotechnical properties, Dr. David Carrier, then at JSC, made the first lunar soil simulant, for drilling research, out of "League City Sand and Kaolinite" (Fig. 1), as

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http://dx.doi.org/10.1016/j.pss.2016.04.005
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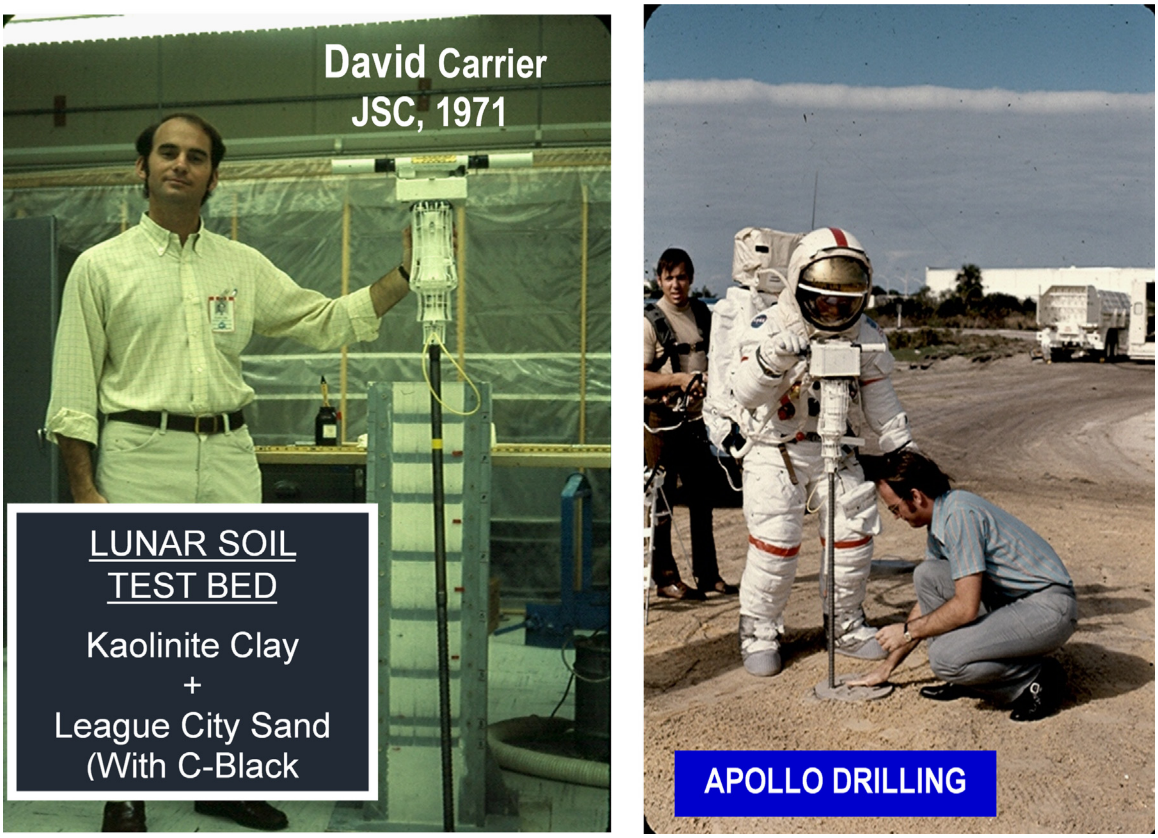

Fig. 1. Young engineer Dr. David Carrier, fresh out of MIT, helping to solve the drilling and coring problems for the Apollo astronauts. (Photo courtesy of David Carrier).

discussed above. This unlikely mixture was tremendously different in composition from anything lunar, yet this strange mixture did the job for the engineers in this specific application.

With the returned Apollo 11 samples, it became apparent that the basalts were extremely high in TiO_2 content (>20 wt%), compared to terrestrial rocks. In January, 1971, at the Second Lunar Science Conference, Prof. Paul Weiblen, of the University of Minnesota, passed out key-rings with small samples of his Minnesota Lunar Simulant (MLS-1; Weiblen and Gordon, 1988; Weiblen et al., 1990). It was crushed basalt from a 1–2 m sill in a quarry in Duluth, MN. It has one of the highest TiO_2 contents of basalts on Earth (6.8 wt%), yet barely half of some of the high-Ti basalts from the Moon (e.g., Apollo 17 basalt 71055 = 13-15 wt% TiO_2). Realizing that lunar soil contained glass, Paul went on to melt portions of this crushed rock in a 4–6000 °C plasma drop-furnace, producing glass, which combined with the raw basalt, was then ground into a Particle Size Distribution (PSD) to resemble lunar soil. The MLS-1 lunar soil simulant, in various sizes and glass contents, was employed by the engineering community for several years. But, it was only meant to have a TiO_2 content to mimic the high-Ti basaltic soils from Apollo 11, not to have correct mineralogy, chemistry, or engineering properties.

Finally in 1993, a new lunar soil simulant (JSC-1) was designed to have a high proportion of natural glass, which gave it more of the properties of the abundant agglutinates in lunar soil. A welded tuff from a quarry north of Flagstaff, AZ was selected, mined, and crushed by Prof. James Carter, and ground to a PSD resembling the lunar soil (McKay et al., 1992, 1994). This simulant was chosen simply because it had $\sim$50% friable glass (cf., agglutinates) and was available in large quantities. It was stated that it had the composition of mare soil, yet it really did not (the simulant resembled the chemistry of some unusual Apollo 14 soils, which were not mare) (Fig. 2). In reality its composition only represents some 2–3% of the lunar surface, but has been used as a 'good' mare-soil simulant for all sorts of uses, including hydrogen reduction of ilmenite, but it has only $<<1\%$ ilmenite. Some 15 tons of JSC-1 were produced and distributed by JSC Curatorial, free to the public. And it was gone quickly. But, the lunar science and engineering community continued to produce new lunar simulants, both here and abroad.

In January, 2004, President Bush set us on a course "to the Moon, then Mars, and Beyond", causing a tremendous rekindling of excitement in the USA about returning to the Moon, also picked up around the world by all the major countries. With this great impetus, Jerry Sanders, head of ISRU and engineering efforts at JSC, initiated a new program at MSFC called Lunar Simulant Production. This was to oversee and control all production of simulants, both in the USA and abroad. It promoted JSC-1A – same simulant from the same quarry. This started out with all good intensions, but soon became more engineering than science, especially lunar science.

Without good input from lunar soil experts, like Dave McKay, the manufacture of lunar simulants has limped along since then. Most of the publications that have resulted have been in government "gray to dark-gray" literature, not readily reviewed or carried by the typical engineering journals (e.g., Gaier, 2008). Hence, without this proper knowledge, the engineers of the world have gone about making NASA's major lunar simulants, duplicating JSC-1 and JSC-1A; recall that these are atypical soils for the Moon. Simulant JSC-1A has been treated by foreign countries as the lunar simulant for all purposes. In fact, there have been several good attempts to even duplicate the trace-element contents of these JSC simulants – for what purpose, who really knows. These have NASA's "stamp of approval", and must be the best – they imagine.

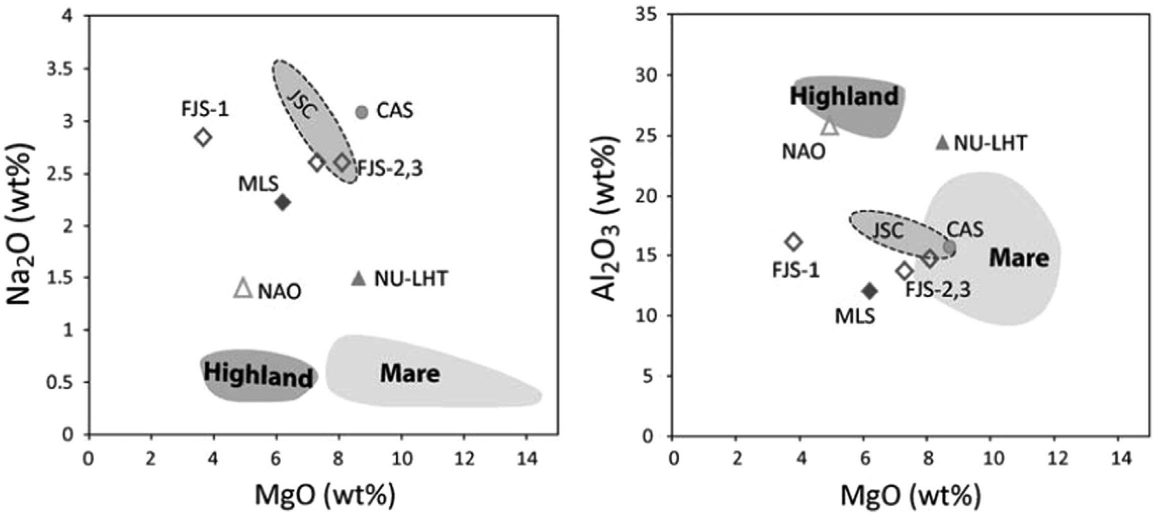

Fig. 2. Bulk compositions of several lunar soil simulants. Notice the disparity between the lunar composition and those of the simulants. Modified after Taylor and Liu (2010).

3. Nanophase metallic iron

A feature that readily distinguishes between lunar rocks and soils and their terrestrial counter-parts is the presence of metallic iron (Fe). The lunar magmas and lavas have such a low partial-pressure of oxygen that native Fe is stable as a mineral, a product of crystallization at low oxygen fugacities (fO_2). However, the metallic Fe in the lunar soil also comes from meteorites; but another source of some of the native Fe took several years for the Apollo scientists to understand, and then it took another two decades before we really understood the origin of a ubiquitous, yet minute-sized metallic Fe – the so-called nanophase Fe (np-Fe). These np-Fe particles were originally called “single-domain” Fe, with sizes of 3–33 nm, because they possess single-domain magnetic properties (Fig. 3). Back in 1973 (Housley et al., 1973), it was reasoned that this np-Fe formed by the auto-reduction of melted lunar soil, saturated with solar-wind protons (hydrogen nuclei). Finally, Keller and McKay (1993, 1997) demonstrated by electron transmission microscopy that these tiny Fe grains were formed by vapor deposition, due to energetic micro-meteoroid impacts (see Fig. 3).

4. Lunar soil cycle

In the formation of lunar soil, micro-meteoroids impacting at velocities of 30–40,000 not only crush and pulverize the lithic fragments, but also melt some of the soil, which acts to stick grains together to form agglutinates. However, with such high velocities (i.e., kinetic energy), the temperature of the melted soil can reach > 2000 °C, and the silicate melt vaporizes, releasing various ions and elements in preferential order. Some of the easiest of the oxides in the soil to vaporize, after Na, K, and S, are SiO_2 and FeO. With such high temperatures, these oxides further dissociate losing their oxygen. These vapors permeate then the immediate vicinity and are deposited as 10–20 nm layers of silica-rich glass with myriads of 3–33 nm sized metallic Fe grains (Fig. 4). These glass rinds, on virtually every soil particle in a mature soil, are brittle and readily crack and become part of the fine particles of the soil (as demonstrated by Taylor et al. 2001, 2010). Some of these elements combine in strange ways, for example to form Hapkeite (Fe_2Si; Anand et al., 2003). Some of this glass becomes part of the agglutinitic glass, where it ripens and increases in size (Pieters and Taylor, 2003).

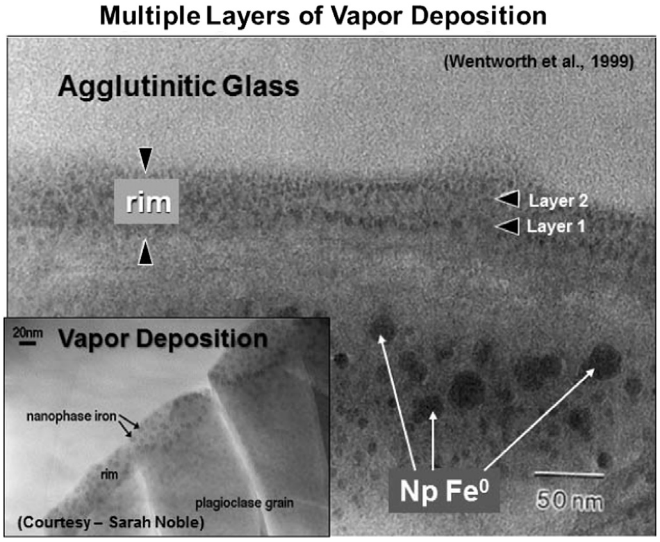

Fig. 3. Examples of np-Fe demonstrating vapor deposition of its formation. Note that the np-Fe in the agglutinate is larger from ripening of the small np-Fe. The surface glass is readily broken off the rinds and becomes part of the finest size fraction that gets melted to form the agglutinitic glass that aggregates the soil particles together.

5. Example of a useless lunar simulant

Lunar soil simulant JSC-1A is a ground volcanic tuff, with ~50% glass (Hill et al., 2007). This is a reasonable simulant for many purposes. Its glass, when examined in detail at high magnification is full of nano-sized Ti-magnetite (Fig. 5), the terrestrial mineral with the highest magnetic susceptibility of all. The major effects that np-Fe has upon reflectance spectroscopy is the reddening of the spectra (e.g., Noble et al., 2001, Pieters et al., 2000). It has been these effects that have dominated the literature about np-Fe, the result of space weathering. Lunar-like simulations of np-Fe in silica-rich glass have successfully been produced in the size range observed in vapor-deposited glass coatings and in agglutinitic glass but only by Noble et al. (2007) and Liu et al. (2007) and the former investigators used the np-Fe to study the effects upon reflectance spectra. However, the engineers have focused in on np-Fe for some other, largely unknown reasons – hence, the manufacture of JSC-1A with np-Fe (Gustafson, 2009). But who needs it? Does it make JSC-1A any more lunar-like? Maybe, but for what use? The making of JSC-1A with np-Fe is an

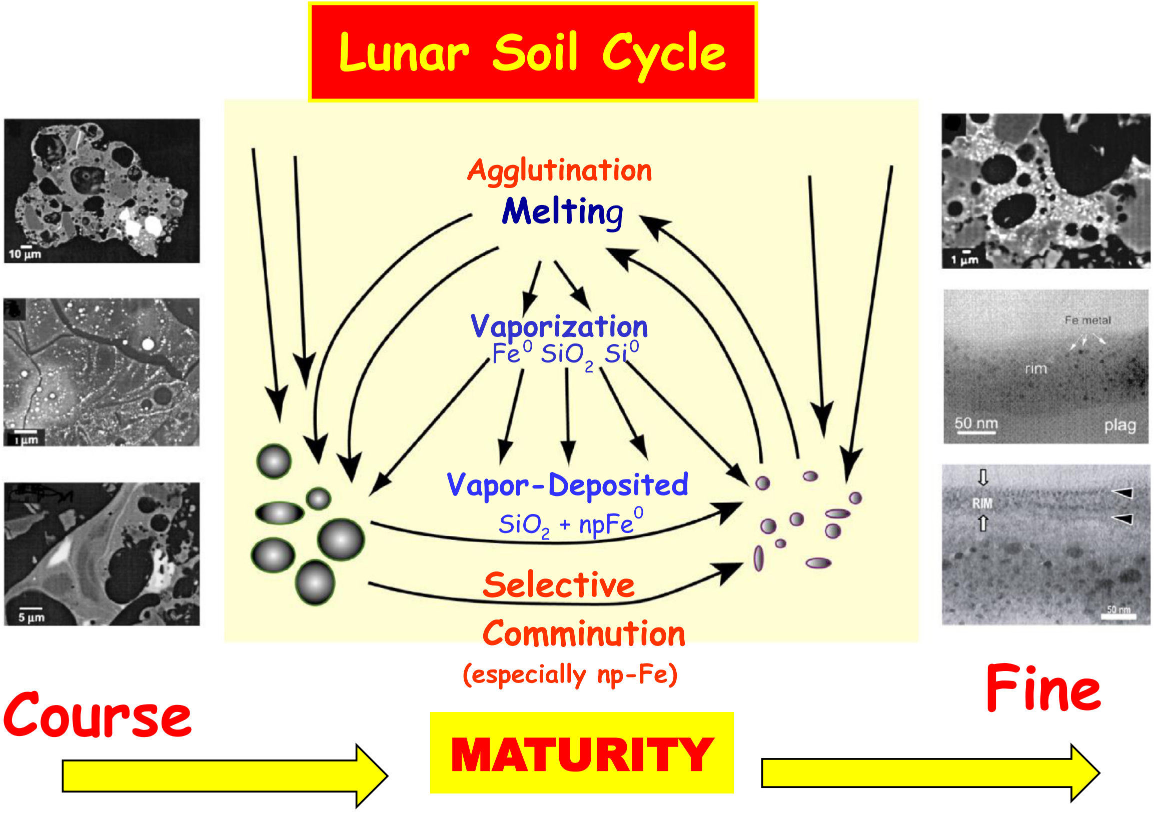

Fig. 4. The senior-author's version of the lunar soil cycle, caused by space weathering. The meteoroid impact make the soil particles smaller, but also cause melting, which is sort of like "taffy on popcorn" in that soil particles are aggregated together to form the agglutinates. And extreme heating causes the melt to effectively boil, freeing up SiO_2 and FeO, which subsequently dissociate to form the vapor that condenses as the silica-rich rinds and np-Fe.

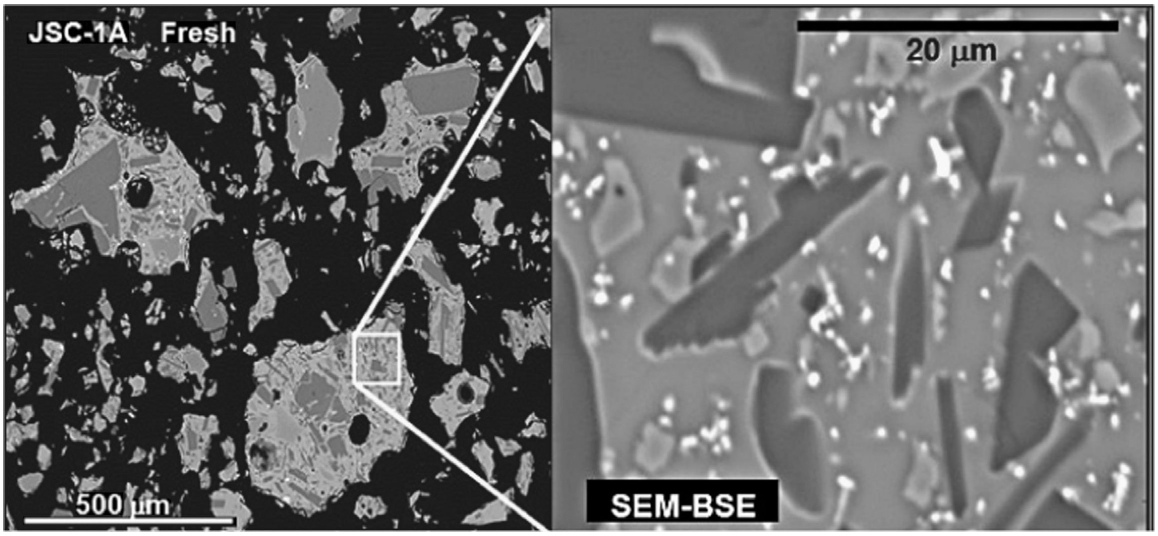

Fig. 5. Scanning electron microscopic, back-scattered electron images of lunar soil simulant JSC-1A. All the tiny white phases are nanophase-sized Ti-magnetite, negating any reason for making nanophase Fe in this simulant. Yet, > $M were spent to making nanophase Fe in this simulant. Yet, > $M were spent to make exactly that: JSC-1A with np-Fe.

excellent example of the engineering group at MSFC not having sufficient scientific input. It cost NASA > $M to produce by SBIR. Yes, the small amount of metallic Fe added to JSC-1A will increase the overall magnetic susceptibility, but for what use is not apparent. Surely not for mineral beneficiation, where the susceptibilities of the mineral components of lunar rocks and soils were studied for use in magnetic beneficiation by Taylor and Oder (1990). This is an example of a lunar soil simulant not needed, but costly in preparation.

6. NRC-PPS request to LEAG-SWG

In 2010, the NASA Advisory Council, through one of its support teams, the Planetary Science Sub-committee requested that the Lunar Exploration Advisory Group (LEAG) have its Science Working Group (SWG) research the status of the lunar simulant production. "The PSS recommends that a comprehensive study be undertaken by LEAG and CAPTEM [Curation and Analysis Planning Team for Extraterrestrial Materials] to define the types of simulants that the various communities require in order to facilitate important lunar investigations as well as to preserve the Apollo lunar sample collection for future generations." (LEAG-CAPTEM SWG, 2010).

This LEAG-CAPTEM group was charged with: identify all available lunar simulants; identify all potential areas of study; etc. The product was to basically address: 1) what is needed for lunar simulants; 2) what lunar simulants already exist; 3) protocols for their proper usage, and 4) needs for Apollo lunar samples.

The SWG committee consisted of representatives from all the different facets of the lunar simulant engineering/science community (Table 1). This cross-fertilization of 'mental calories' led to many hearty and worthwhile discussions. It was decided that we need to have the users define what simulants are important for testing. Hardware developers have tended to make their own simulants (Table 2). We tried to discourage this activity, but this has not come to pass. Basically it is NASA's responsibility to collect all the necessary needs for simulants and categorize it for the community at large. *It is essential that scientific peer-reviewed journals be utilized for distribution of information on extra-terrestrial simulants, not in 'gray', non-peer reviewed, government literature. It is essential that scientific peer-reviewed journals be utilized for distribution of information on extra-terrestrial simulants, not in 'gray', non-peer reviewed, government literature.*

Table 1
Members of the LEAG-CAPTEM SWG for Lunar Simulant Study.

LEAG-CAPTEM Simulant Working Group (2010)
Working group members [Chip Shearer (ex-officio) LEAG Chair]:
Larry Taylor, Univ. of Tenn., LADTAG, Lunar Soil Expert (Chair)
Jennifer Edmunson, MSFC, Simulant Engr.
Bob Ferl, Univ. of Florida, Bio Expert
Bob Gustafson – ORBITEC, Simulant Engr.
Yang Liu, Univ. of Tenn., Lunar Soil & Simulant Characterizer
Gary Lofgren, JSC, Lunar Sample Curator
Carole McLemore, MSFC, ISRU/Dust Project Manager
Dave McKay, JSC, LADTAG, Lunar Soil Expert (Dust/Biomedical)
Doug Rickman, MSFC, Simulant developer and tester
Jerry Sanders, JSC, ISRU Head Honcho
Mini Wadhwa, CAPTEM Chair, Lunar Expert

The SWG presented its report to the PPS and is entitled: "**Status of Lunar Regolith Simulants and Demand for Apollo Lunar Samples**". This report in all its detail is available at http://www.lpi.usra.edu/leag/reports/SIM_SATReport2010.pdf.

Although not in this report, the feelings of the present authors and many others of the SWG were *that the Lunar Simulant Program presently at MSFC be re-established at JSC as the "Extra-Terrestrial Simulants Program"*. After all, JSC, starting with the Apollo samples, has focused upon the science and curation of planetary materials, including those from the Moon, Mars, Asteroidal Meteorites, including the Antarctic Collections, and is the recognized center for all such activities, including preparing for the return of Martian rocks and soils. The Head of all ISRU activities for NASA, Jerry Sanders, is also at JSC and can insure the proper balance between the scientists and engineers, so that funds are not wasted on non-useable simulants.

7. Apollo lunar soil for ISRU experiments

During the Apollo 17 Mission on December 12–14, 1972, this author was in the "backroom" at Johnson Space Center, along with two dozen other scientists, giving advice, through CATCOM, to Astronauts Jack Schmitt and Gene Cernan during their planned EVAs (extra-vehicular activity) on the Moon. During the removal of the Lunar Rover Vehicle (LRV), prior to the first EVA, the fender on the right-rear was broken off. Imagine riding down a rain-soaked street without any rear fender, and the streak down your back. With the extreme vacuum (10^{-15} atm) of the Moon, the "Rooster's Tail" that was partially thrown up in front of the LRV was too much. For EVA 2, geologist Jack fashioned a rear fender with a geologic map, a clamp, and 'duct tape'. It worked fairly well, yet the soil continued to pile up on the battery packs on the rear of the LRV, necessitating cleaning this loose soil off the packs several times in order to keep

Table 2
List of lunar regolith (soil) simulants and their purposes.

Lunar regolith simulants worldwide	Type
MLS-1* Minnesota Lunar Simulant (Weiblen et al., 1990)	High-Ilmenite mare (general use)
MLS-1P* (Weiblen et al., 1990)	High-Ti mare (exper., not in bulk)
MLS-2*	Highlands (general use)
ALS Arizona Lunar Simulant	Low-Ti Mare (geotechnical)
JSC-1* Johnson Space Center, (McKay et al., 1994)	Low-Ti mare (general use)
FJS-1 (type 1) Fuji Japanese Simulant (Kanamori et al., 1998)	Low-Ti mare
FJS-1 (type 2)	Low-Ti mare
FJS-1 (type 3)	High-Ti mare
MKS-1 MSFC	Low-Ti mare (intended use unknown)
JSC-1A, -1AF anonymous, undated, http://www.orbitec.com/store JSC-1A-Bulk-Data-Characterization.pdf	Low-Ti mare (general use) (JSC-1A produced from same source)
OB-1 Olivine-Bytownite (Richard et al., 2007)	Highlands (general use geotechnical)
CHENOBI undocumented, see http://www.evcltd.com/ index.html	Highlands (geotechnical)
CAS-1 (Zheng et al., 2008)	Low-Ti mare (general use)
GCA-1 Goddard Space Center (Taylor et al., 2008)	Low-Ti mare (geotechnical)
NU-LHT-1M & 1D NASA/USGS-Lunar Highlands Stoeser 2007	Highlands (general use)
NU-LHT-2M & 2C (Stoeser and Wilson, 2007)	Highlands (general use)
Oshima base simulant	High-Ti mare (general use)
Kohyama base simulant	Intermediate; highlands & mare
NAO-1 (Li et al., 2008)	Highlands (general use)
CLRS-1 Chinese Lunar Reg. Sim., Chinese Acad. of Sciences	Low-Ti mare (general use?)
CLRS-2 Chinese Academy of Sciences	High-Ti mare (general use?)
CUG-1 Chinese Academy of Sciences	Low-Ti mare (geotechnical)
GRC-1 & -3 Glenn Research Center	Geotech. std. vehicle mobility simulant
TJ-1 Tongji University	Low-Ti mare (geotechnical)
TJ-2	
KOHLS-1 Koh Lunar Simulant	Low-Ti mare (geotechnical)
BP-1 Black Point, (Rahmatian and Metzger, 2010)	Low-Ti mare (geotechnical)
CSM-CL Colorado School of Mines – Colorado Lava	Geotechnical

Table 3
Composition of glasses and major mineral phases in 70051.

	Aggl. glass	Vol. glass	Augite	Pigeonite	Pyroxene	Plagioclase	Olivine	Ilmenite
SiO_2	45.2 (37)*	38.9 (12)	49.9 (11)	51.3 (7)	54.2 (15)	44.6 (9)	38.5 (15)	52.8 (4)
TiO_2	3.27 (277)	9.51 (80)	1.34 (65)	0.82 (85)	0.48 (15)	0.05 (4)	0.09 (5)	0.04 (3)
Al_2O_3	16.2 (51)	6.15 (12)	1.74 (29)	1.68 (14)	0.95 (36)	34.4 (125)		
Cr_2O_3	0.22 (15)	0.64 (23)	0.47 (21)	0.50 (31)	0.43 (19)		0.05 (7)	0.68 (12)
FeO	11.6 (46)	21.6 (22)	16.2 (39)	18.1 (12)	13.1 (68)	0.22 (19)	20.2 (78)	42.8 (7)
MgO	8.31 (296)	13.1 (26)	14.6 (23)	21.0 (2)	27.9 (51)	0.11 (10)	40.3 (64)	2.34 (45)
CaO	12.5 (18)	8.24 (152)	14.2 (37)	5.00 (41)	1.71 (23)	19.0 (7)	0.16 (13)	0.10 (11)
Na_2O	0.51 (36)	0.31 (29)	0.87 (4)			0.59 (37)		
K_2O	0.14 (26)	0.07 (7)				0.08 (6)		0.04 (1)
Total	**98.0**	**98.5**	**99.3**	**98.4**	**98.8**	**99.1**	**99.6**	**99.2**

One sigma variance in the analysis in () in terms of the least unit cited.

the temperature down in the batteries. At the end of the third and final EVA, Jack noticed that there was still a pile of soil on the back of the LRV near the battery pack, especially on the "Buddy Secondary Life Support System", a space life-support pack in case of an emergency. What to do with it? "Bag it up and label it "BSLSS", was the command from CAPCOM". Fast-forward 34 years, and I am in dire need of some lunar soil for my microwave experiments (Taylor and Meek, 2005). Having been on several lunar sample appropriation committees for a dozen years, I knew only too well the difficulty in getting lunar samples for ISRU. An epiphany comes to me. "The BSLSS bag!" It lacks scientific provenance, being a stochastic mixture of soils from various portions of the entire Apollo 17 EVA fieldtrip trails. I request it, and it takes NASA lunar curatorial months to track it down, stored away at remote storage at Arlington Air Force Base, as a "Contingency Lunar Sample".

Subsequently, this 'soil' sample (the portion of regolith <1 cm) was relabeled 70050 and is >2.2 kg (Hill et al., 2007). Lunar soils are typically sieved into size fractions, such that 70051 is everything <1 mm, 70052 is 1–2 mm, 70053 is 2–4 mm, and 70054 is 4–10 mm. Hence the <1-mm portion was labeled as 70051, with a total of 1438 g. Table 3 presents the details on the mineral and glass components for 70051 from the work of Hill et al. (2007). As a sample collected from the back of the lunar rover, it lacks the scientific integrity of provenance, but does represent a haphazard mixture of fractions of lunar soils from all over the EVA trails, particularly the third. It contains both mare and highland lithologies, especially since it came near the bottom of the South Massif.

The evaluation team (CAPTEM) for NASA's Extra-terrestrial Curation at JSC will gladly entertain proposals for use of this unusual soil (70050 and its splits). However, it must be appreciated by the ISRU engineers that the experimental and or analytical techniques that you wish to employ must be miniaturized, in order to use the smallest amount of lunar soil.

8. Summary

This paper focusses on the formation of lunar soil with the introduction of a lunar soil cycle, actually applicable to all airless bodies. It also addresses the production lunar regolith simulants, their history, their production, their use and misuse, especially with respect to the manufacture of nanophase metallic (np-Fe). It is shown that *JSC-1A has only limited use, and there is nothing special with it other than its high content (~50%) of fragile glass* (Hill et al., 2007). The incorporation of np-Fe into JSC-1A is used to emphasize that this costly simulant production was totally unnecessary.

In 2010, LEAG-CAPTEM SWG prepared a report for NASA NAC–PSS. This entailed a list of all simulants known at that time, and illustrated the critical need for more lunar soil science education of the engineers making these simulants, and the evaluation that the Lunar Simulant Program at MSFC needed rejuvenation. It is considered by the authors and others that this simulant program should be moved to JSC, where all planetary materials are curated and studied. This endeavor might be united with the existing planetary material curation facility as the "Extra-terrestrial Simulants Program, and with the Head of NASA's ISRU program, in residence at JSC, as coordinator".

The collection of a little-known soil sample, 70050, collected off of the BSSLS unit on the back of the Apollo 17 LRV lacks provenance for good science research. However, it represents a lunar soil with particles thrown up from all along EVA 3, and contains mare and highland fragments, as well as their soil, but all mixed together. It represents a "low-grade lunar soil" of possible use for certain ISRU endeavors.

Acknowledgments

This paper was collectively funded by two SSERVI teams: **SEEED** – "SSERVI Environment and Evolution of Exploration Destinations (SEEED)" to Prof. Carlé M. Pieters at Brown University [SSERVI NNA14AB01A] and **CLASS** – "Center for Lunar and Asteroid Surface Science" to Prof. Dan Britt at the University of Central Florida [SSERVI NNA14AB05A]. In addition, Dr. Dawn Taylor is gratefully acknowledged for her typical fine assistance with preparation of this manuscript, a task that will cost the senior author a fine dinner.

References

Anand, M., Taylor, L.A., Nazarov, M.A., Shu, J., Mao, H.-K., Hemley, R.J., 2003. New lunar mineral HAPKEITE: product of impact-induced vapor-phase deposition in the regolith? Lunar Planet. Sci. XXXIV, LPI CD- ROM #1818.

Gaier, J.R., 2008. The need for high fidelity lunar regolith simulants. NASA/TM-2008-215261.

Gustafson, G., 2009. JSC-1A lunar regolith simulant: availability and characterization. In: Proceedings of Workshop on Lunar Regolith Simulant. http://isru.msfc.nasa.gov/2009wksp_docs.html.

Hill, E., Mellin, M.J., Deane, B., Liu, Y., Taylor, L.A., 2007. Apollo sample 70051 and high- and low-Ti lunar soil simulants MLS-1A and JSC-1A: implications for future lunar exploration. J. Geophys. Res. 112, E02006.

Housley, R.M., Grant, R.W., Paton, N.E., 1973. Origin and characteristics of excess Fe metal in lunar glass welded aggregates. In: Proceedings of the 4th Lunar Science Conference, pp. 2737–2749.

Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto, S., Takagi, K., 1998. Properties of lunar soil simulant manufactured in Japan. In: Proceedings of the International Symposium Space 98, ASCE, Reston, Va., pp. 462–468.

Keller, L.P., McKay, D.S., 1993. Discovery of vapor deposits in the lunar regolith. Science 261, 1305–1307.

Keller, L.P., McKay, D.S., 1997. The nature and origin of rims on lunar soil grains. Geochim. Cosmochim. Acta 61, 2331–2340.

LEAG-CAPTEM SWG Report, 2010. Status of lunar regolith simulants and demand for Apollo samples. 〈http://www.lpi.usra.edu/leag/reports/SIM_SATReport2010.pdf〉.

Li, Y., Liu, J., Yue, Z., 2008. NAO-1: lunar highland soil stimulant developed in China. J. Aerosp. Eng. 22, 53–57.

Liu, Y., Taylor, L.A., Thompson, J.R., Park, J.S., 2007. Unique properties of lunar impact glass: simulating nanophase iron in agglutinitic glass. Am. Mineral. 92, 1420–1427.

McKay, D.S., Carter J.L., Boles, W.W., Allen, C.C., Allton, J.H., 1992. JSC-1: a new lunar soil simulant. Space IV, ASCE, pp. 857–866.

McKay, D.S., J.L., Carter, W.W., Boles, C.C., Allen, J.H., Allton, 1994. JSC-1: a new lunar soil stimulant, in engineering, construction, and operations in space IV. In: Galloway, R. G., Lokajvol, S.(Eds.), American Society of Civil Engneering. vol. 1, Reston, VA., pp. 857– 866.

Noble, S.K., Pieters, C.M., Taylor, L.A., Morris, R.V., Allen, C.C., McKay, D.S., Keller, L.P., 2001. The optical properties of the finest fraction of lunar soil: implications for space weathering. Meteorit. Planet. Sci. 36, 31–42.

Noble, S.K., Pieters, C.M., Keller, L.P., 2007. An experimental approach to understanding the optical effects of space weathering. Icarus 192, 629–642.

Pieters, C.M., Taylor, L.A., 2003. Systematic mixing and melting in lunar soil evolution. Geophys. Res. Lett. 30, 202048. http://dx.doi.org/10.1029/2003GL018212.

Pieters, C.M., Taylor, L.A., Noble, S.K., Keller, L.P., Hapke, B., Morris, R.V., Allen, C.C., Wentworth, S., 2000. Space weathering on airless bodies: resolving a mystery with lunar samples. Meteorit. Planet. Sci. 35, 1101–1107.

Rahmatian, L., Metzger, P., 2010. Soil test apparatus for lunar surfaces. In: Proceedings of Earth and Space. pp. 239–253. http://dx.doi.org/10.1061/41096(366)25.

Richard, J., Sigurdson, L., Battler, M.M., 2007. OB-1 lunar highlands physical simulant evolution and production. 2007 Lunar and dust regolith simulant workshop. http://isru.msfc.nasa.gov/2007wksp_docs. html.

Stoeser, D., Wilson, S., 2007. NU-LHT-1M pilot highlands simulant & simulant requirements. Lunar Dust/Regolith Simulant workshop. http://isru.msfc.nasa.gov/2007wksp_docs.html.

Taylor, L.A., Liu, Y., 2010. Important considerations for lunar soil simulants. In: Proceedings of ASCE Earth and Space 2010: Engineering, Science, Construction and Operations in Challenging Environments. pp. 106–118.

Taylor, L.A., TT, Meeks, 2005. Microwave sintering of lunar soil: Properties, theory, and practice. Jour. Aerosp. Engr. 18, 188–196.

Taylor, L.A., Oder, R.R. 1990. Magnetic b eneficiation of highland and hi-Ti mare soils: rock, mineral, and glassy components. In: Proccedings of Space 90 on Engineering, Construction, and Operations in Space II, vol. 1, pp. 143–152.

Taylor, L.A., Pieters, C.M., Keller, L.P., Morris, R.V., McKay, D.S., 2001. Lunar mare soils: space weathering and the major effects of surface - correlated nanophase Fe. J. Geophys. Res. 106 27,985-27,999.

Taylor, L.A., Pieters, C.M., Patchen, A., Taylor, D.-H.S., Morris, R.V., Keller, L.P., McKay, D.S., 2010. Mineralogical and chemical characterization of lunar highland soils: Insights into the space weathering of soils on airless bodies. J. Geophys. Res., 115. http://dx.doi.org/10.1029/2009JE003427.

Taylor, P.T., Lowman, P.D., Nagihara, S., Milam, M.B., Nakamura, 2008. Jurassic diabase from Leesburg. A proposed lunar simulant, VA, p. 2054.

Weiblen, P.W., Gordon, K.L., 1988. Characteristics of a simulant for lunar surface materials. In: Proceedings of the 21st Century Symposium on Lunar Bases and Space Activities, Paper No. LBS-88-213. Houston.

Weiblen, P.W., Murawa, M.J., Reid, K.J., 1990. Preparation of simulants for lunar surface materials. In: Proceedings of the American Society of Civil Engineers in Space II. pp. 98–106.

Zheng, Y., Wang, S., Ziyuan, O., Zou, Y., Liu, J., Li, C., Li, X., Feng, J., 2008. CAS-1 lunar soil simulant. Adv. Space Res. 43, 448–454.