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JSC-1: A NEW LUNAR SOIL SIMULANT

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Abstract

A new lunar soil simulant, JSC-1, has been developed and characterized under the auspices of the NASA Johnson Space Center. This simulant was produced in large quantities to satisfy the requirements of a variety of scientific and engineering investigations. JSC-1 is derived from volcanic ash of basaltic composition, which has been ground, sized, and placed into storage. The simulant's chemical composition, mineralogy, particle size distribution, specific gravity, angle of internal friction, and cohesion have been characterized and fall within the ranges of lunar mare soil samples. JSC-1 is available for only the cost of shipping.

Introduction

The Lunar Simulant Working Group at Space 92 identified the need for large quantities of material to be used in engineering studies of the lunar soil. The previous year the report of the Workshop on Production and Uses of Simulated Lunar Materials concluded: "Simulants of lunar rocks and soils with appropriate properties, although difficult to produce in some cases, will be essential to meeting the system requirements for lunar exploration" (McKay and Blacic, 1991). In order to address this need, a new simulant has been developed under the auspices of the NASA Johnson Space Center. JSC-1 is a glass-rich basaltic ash which approximates the chemical composition, mineralogy, particle size distribution, and engineering properties of lunar mare soil.

JSC-1 was produced specifically for large- and medium-scale engineering studies in support of future human activities on the Moon. Such studies include material handling, construction, excavation, and transportation. The simulant is also appropriate for research on dust control, spacesuit durability, and agriculture. JSC-1 is currently being used in studies of oxygen production and sintering. The simulant is available in large quantities to any qualified investigator.

This material complements, but does not replace, lunar simulant MLS-1, produced by the University of Minnesota (Weiblen et al, 1990). MLS-1 is derived from a high-titanium basalt hornfels which approximates the chemical composition of Apollo 11 soil. The starting material is totally crystalline. As described below, JSC-1 approximates a low-titanium mare soil, and contains a high percentage of glass.

Source

JSC-1 was mined from a volcanic ash deposit located in the San Francisco volcano field near Flagstaff, AZ. This ash was erupted from vents related to Merriam Crater (35°20' N, 111°17' W). One basalt flow from a nearby vent has a K-Ar age of 0.15 ± 0.03 million years. The exposure is described as "airfall ash and lapilli, usually black, locally red, as much as several meters thick ... (which) forms broad, smooth-surfaced deposits over large areas" (Moore and Wolfe, 1987). The source quarry is within an area mapped by these authors as "slightly porphyritic basalt".

Preparation

The ash was mined from a commercial cinder quarry near the south flank of Merriam Crater. Following coarse sieving the ash was comminuted in an impact mill. This method broke down the material by means of multiple impacts with other ash particles, resulting in minimal metal contamination. The ash from several millings was allowed to partially dry in air and was then mixed. The average water content of the final mix was 2.70 ± 0.31 wt. %. The material, in 45 - 50 lb quantities, was loaded into plastic bags and the bags were heat sealed.

Characterization

Chemical Composition

The results of x-ray fluorescence (XRF) analysis are presented in Table 1. Samples were allowed to dry in air for approximately two months prior to analysis. The crushed rock was ground to pass an 80 mesh (177 µm) sieve. Oxide abundances, loss on ignition, and Fe2O3 / FeO partitioning were determined by the methods of Boyd and Mertzman (1987).

The loss on ignition (LOI) value was derived by heating samples in argon for one hour at 900°C. This value reflects the loss of volatiles, including water as well as sulfur and chlorine compounds. The analyses were performed on well-dried samples, and reflect lower water contents than those of samples from newly-opened bags.

Table 1: Major Element Compositions

	JSC-1 (mean of 3)		Lunar Soil 14163*
Oxide	**Conc.**	**Std. Dev.**	**Conc.**
	Wt %	**Wt %**	**Wt %**
SiO2	47.71	0.10	47.3
TiO2	1.59	0.01	1.6
Al2O3	15.02	0.04	17.8
Fe2O3	3.44	0.03	0.0
FeO	7.35	0.05	10.5
MgO	9.01	0.09	9.6
CaO	10.42	0.03	11.4
Na2O	2.70	0.03	0.7
K2O	0.82	0.02	0.6
MnO	0.18	0.00	0.1
Cr2O3	0.04	0.00	0.2
P2O5	0.66	0.01	---
LOI	0.71	0.05	---
Total	**99.65**		**99.8**

LOI = Loss on ignition * Papike et al (1982)

The trace element concentrations in JSC-1 are listed in Table 2. These data were averaged from instrumental neutron activation analyses (INAA) performed on three samples. The samples, loaded into pure silica tubes, were irradiated the University of Missouri Research Reactor Facility for 20 hours each at a flux of 7.6 x 1013 n/cm2-sec. Counting and data reduction were performed at the Johnson Space Center.

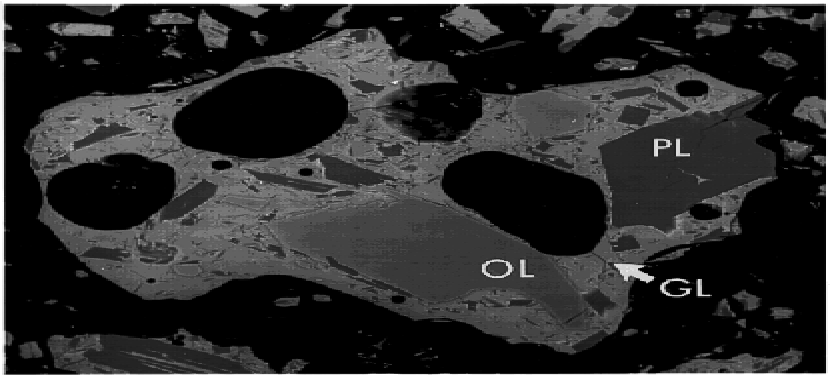
Table 2. Trace Element Concentrations in JSC-1

Element	Conc. (ppm)	Std. Dev. (ppm)	Element	Conc. (ppm)	Std. Dev. (ppm)

Sc	29.2	0.5	Yb	1.99	0.04
Co	47.7	1.6	Zr	125	3
Ni	137	18	Hf	3.55	0.08
Rb	12.3	1.5	Ta	1.96	0.04
Cs	0.339	0.012	U	1.51	0.08
Sr	860	36	Th	5.65	0.07
Ba	822	13	As	18.7	8.9
La	48.2	0.9	Se	< 0.5	0.0
Ce	94.6	1.7	Sb	0.564	0.569
Nd	42	2	W	36.1	2.6
Sm	7.44	0.13	Au (ppb)	40.7	29.4
Eu	2.18	0.04	Br	0.85	0.07
Tb	0.825	0.012	Lu	0.293	0.007

Mineralogy

The major mineral species in JSC-1 samples were identified by x-ray diffraction (XRD), optical microscopy, and scanning electron microscopy (SEM). Qualitative elemental abundances were determined for some SEM samples by energy-dispersive x-ray spectrometry (EDS). The major crystalline phases are plagioclase, pyroxene and olivine. Minor minerals include the oxides ilmenite and chromite, plus traces of clay. The glass and minerals in a typical grain are shown in Figure 1.



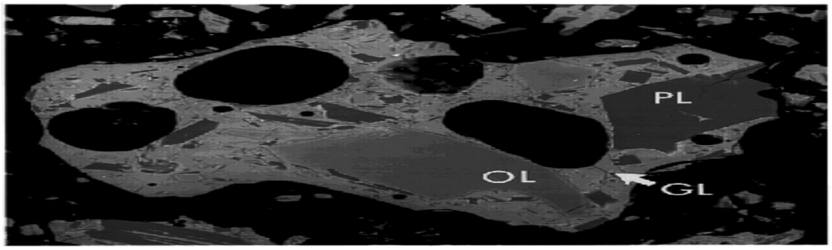


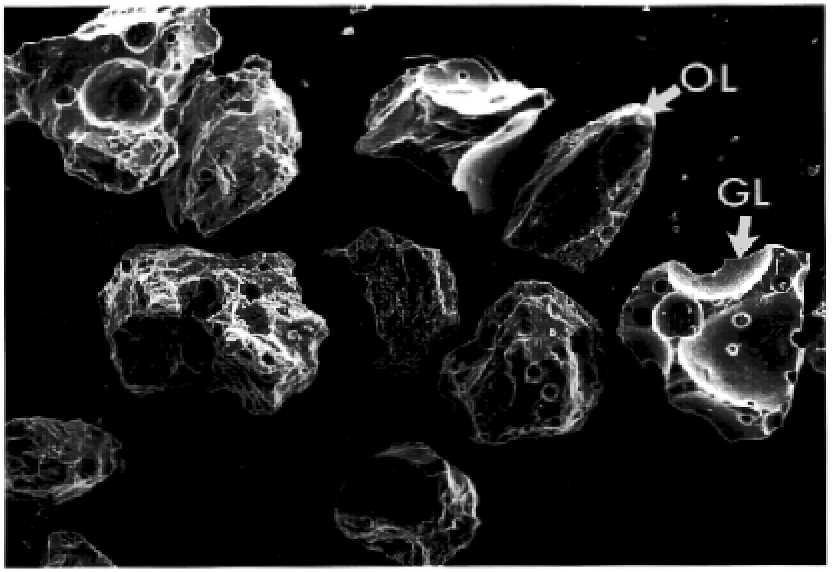
Figure 1. JSC-1 grains in polished section.
Phases include glass (GL), plagioclase (PL) and olivine (OL).
SEM back-scattered electron image. Frame width = 520 µm.

The plagioclase crystals are needle-shaped or blocky, as large as several hundred micrometers. Pyroxene and olivine crystals are blocky to subrounded, and up to 100 µm across. Ilmenite and chromite occur as swarms of rounded crystals, each less than 10 µm in diameter.

Approximately half of the volume of a typical particle is glass of basaltic composition. Much of this glass contains plagioclase needles and oxide minerals a few micrometers in size.

Particle Description

Scanning electron micrographs show broken glass and mineral fragments as large as several hundred micrometers (Figure 2). Glassy particles invariably display broken vesicles with sharp edges. Mineral fragments are angular to sub-rounded, and many show the scars of impacts from the milling process.



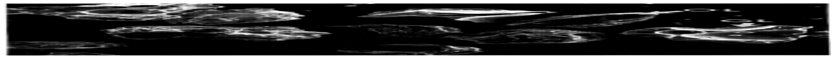


Figure 2. JSC-1 glass (GL) and olivine (OL) grains.
SEM secondary electron image. Frame width = 1100 µm.

Particle Size Distribution

Two particle size distribution curves for JSC-1 are presented in Figure 3. In work done at the University of Texas, Dallas (UTD curve), fifteen 250 g splits were analyzed. The samples were initially sieved dry, wetted to remove adhering fines, dried, and resieved. Finally, the weight per cent smaller than a given sieve opening was computed.

An independent analysis at the Johnson Space Center (NASA curve) followed procedures developed for lunar soil samples (McKay et al, 1974). Four 25 g splits were mixed, and a 15 g subsample was separated. This material was sieved while being wetted with freon.

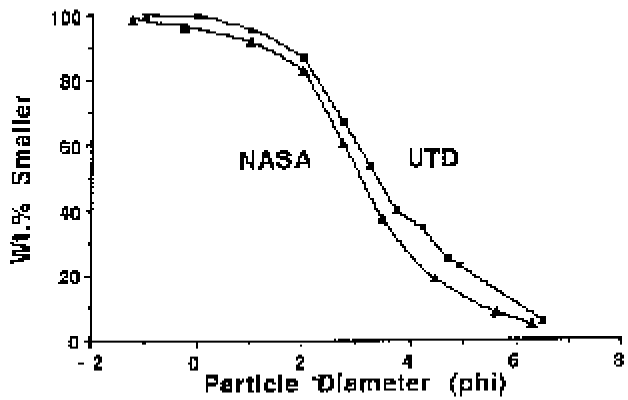


Figure 3. Particle size distribution curves for JSC-1.
Particle diameters in phi units (¯ = - (ln d) / (ln 2), d = diameter in mm).

The median particle sizes for these samples, defined such that 50% of the soil is larger and 50% is smaller, equal 98 µm (UTD) and 117 µm (NASA). The mean particle sizes, defined as the average of the diameters at 16, 50 and 84 wt. % smaller on the curves (Figure 3), equal 81 µm (UTD) and 105 µm (NASA). The similarity of results from the two methods provides confidence in the large-scale sample homogeneity.

Specific Gravity

The average specific gravity of JSC-1 particles is 2.9 g/cm3. This value is the ratio of particle mass to the mass of an equal volume of water measured at 4°C. Specific gravity was determined using the method of Lambe and Whitman (1969).

Angle of Internal Friction and Cohesion

The angle of internal friction for JSC-1 is approximately 45° and the cohesion of the material is approximately 1.0 kPa. These values were determined from the Mohr-Coulomb failure criterion as described by Das (1985). Samples were run in a triaxial cell and tested at confining pressures of 5, 10, and 15 psi (Turk, 1992). As shown in Figure 4, the failure envelope may be slightly nonlinear. If so, low confining pressures yield a higher angle of internal friction and lower cohesion, and vice versa.

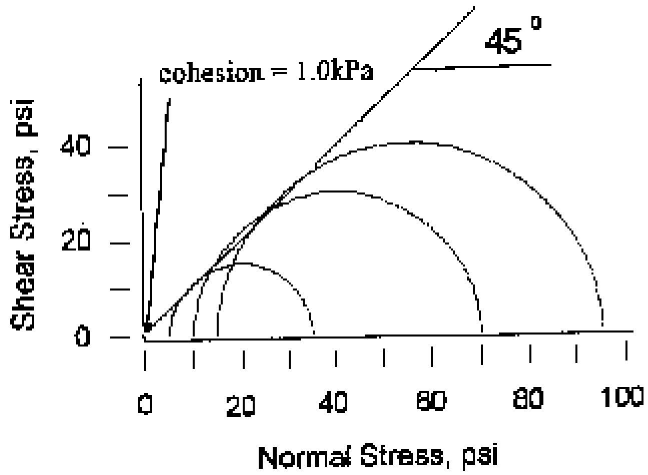


Figure 4. Mohr stress circles used to determine angle of internal friction (45°) and cohesion (1.0 kPa) for JSC-1.

Comparison to Lunar Soils

Chemical Composition

JSC-1 is a basaltic ash with a composition typical of many terrestrial basalts. Lunar basalts, and the mare soils derived from them, are generally similar to JSC-1 in major element composition. Lunar samples, however, contain no water and have low abundances of volatile oxides such as Na2O. In addition, lunar rocks were formed in highly reducing environments and contain iron only as Fe2+ and Fe0. These differences are illustrated in Table 1, which compares the composition of JSC-1 to that of Apollo 14 soil 14163 (Papike et al, 1982).

Mineralogy

The minerals found in JSC-1, plagioclase, pyroxene, olivine, ilmenite, and chromite, are also characteristic of many lunar basalts and mare soils (Figure 5). The compositional ranges of these lunar minerals generally overlap the ranges of their terrestrial counterparts.

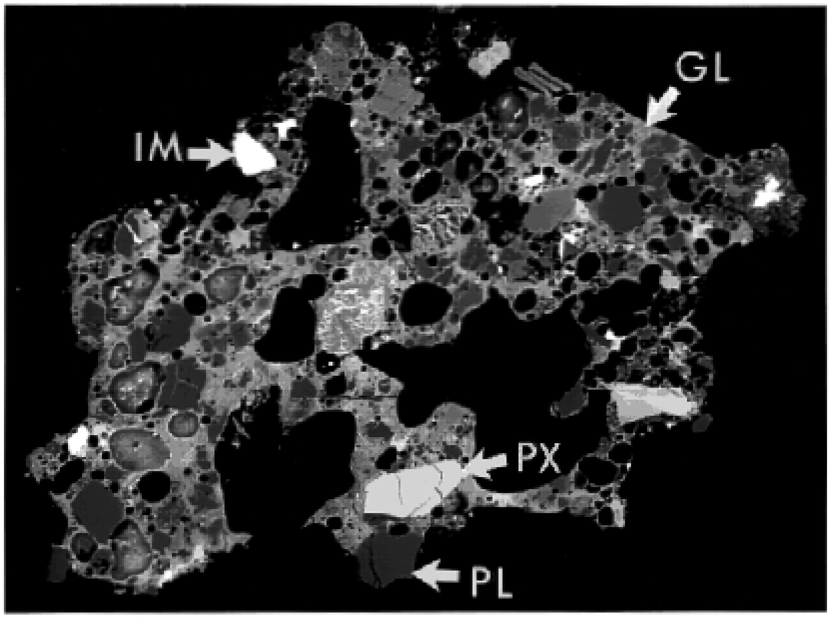


Figure 5. Lunar mare soil grain (78221,8) in polished section.
Phases include glass (GL), plagioclase (PL), pyroxene (PX), and ilmenite (IM).
SEM back-scattered electron image. Frame width = 660 μm.

Lunar soil also contains a significant component of glass produced by micrometeorite impact. This "agglutinitic" glass was apparently formed under highly reducing conditions, as it invariably contains submicrometer particles of native iron metal. The volcanic glass component of JSC-1 contains more micrometer-scale plagioclase and metal oxide crystals than lunar impact glass, but the JSC-1 glass contains no iron metal.

Particle Description

Lunar soil is a complex mixture of rock and mineral grains shattered by impact, along with impact-derived glass. This agglutinitic glass bonds the rock and mineral fragments into submillimeter particles which are characteristic of most lunar soils (Figure 5). Such particles constitute over half of the volume of many soil samples. The micrometer-scale textures of lunar agglutinates are extremely complex, and are not precisely matched by any terrestrial analog.

Particle Size Distribution

JSC-1 is similar in particle size distribution to a typical submature lunar soil, such as Apollo 15 soil 15530 with a median particle size of 102 μm. Mean and median particle size ranges from Apollo soil samples are compared in Table 3.

Table 3. Mean and Median Particle Sizes

Sample	Size Range (µm)
JSC-1 (median - UTD)	98
JSC-1 (median - NASA)	117
JSC-1 (mean - UTD)	81
JSC-1 (mean - NASA)	105
Apollo 11 (median)*	48 - 105
Apollo 12 (median)*	42 - 94
Apollo 14 (median)*	75 - 802
Apollo 15 (median)*	51 - 108
Apollo 16 (mean)*	101 - 268
Apollo 17 (mean)*	42 - 166

*(McKay et al, 1991; Table 7.8)

JSC-1 grains are better sorted, i.e., have a narrower particle size distribution, than most lunar soils. However, several samples, such as Apollo 14 soil 14230 and Apollo 17 core 74002, have comparably high degrees of sorting.

An extensive compilation of 143 lunar soil particle size distributions has recently been published by Graf (1993). Investigators desiring to compare JSC-1 to a specific soil sample should consult this volume.

Specific Gravity

The specific gravity values for lunar soil samples range from 2.9 - 3.5 g/cm3 (Carrier et al, 1991). The JSC-1 value, 2.9 g/cm3, falls on the low end of this range.

Angle of Internal Friction and Cohesion

The angle of internal friction for lunar soil samples ranges from 25° - 50° (Carrier et al, 1991). The cohesion values for these samples ranges from 0.26 - 1.8 kPa (Carrier et al, 1991). JSC-1, with values of 45° and 1.0 kPa, respectively, is a good mechanical analog to lunar soil.

Current Research

Experiments in oxygen production and sintering using JSC-1 are reported in this volume (Allen and McKay, 1994; Allen et al, 1994). Research programs are underway at several universities to characterize the simulant's engineering and thermal properties, gas evolution, density variations, and changes due to thermal cycling. Quantities of JSC-1 have also been distributed to investigators studying new lunar rover and spacesuit designs, the effects of dust on telescope mirrors, and the bearing capacity of lunar soil.

Availability

Approximately 27,000 lb of JSC-1 simulant is currently available for distribution to qualified investigators. The only cost is for shipping. The material is stored at the Texas A&M Lunar Soil Simulant Laboratory. Investigators desiring a portion of this simulant should address their requests to Dr. Walter Boles, Department of Civil Engineering, Texas A&M University, College Station, TX 77843 (Telephone 409-845-2493, fax 409-862-2800).

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