GUIDE TO USING LUNAR SOIL AND SIMULANTS FOR EXPERIMENTATION

J. H. Allton, C. Galindo Jr., and L. A. Watts

Northrop Services, Inc., P.O. Box 34416, Houston, TX 77234

The vision of a lunar base has stimulated experimentation needed for the planning and construction of lunar vehicles, habitats, and factories. The following discussion is a guide to facilitate the design and interpretation of technology experiments on lunar soil and lunar soil simulants. Lunar soil, once it is taken from the Moon for study in the laboratory, may not represent true *in situ* lunar conditions. The proposed simulated soils are different from genuine lunar soils in several important respects, mostly due to the effects of micrometeorites and solar wind on the Moon. However, these proposed simulants do replicate the lunar soil grain size distribution, gross mineralogy, and general chemical composition and are useful for studies of these properties. There are several reserves of lunar material that are suitable for tests requiring genuine lunar soil.

INTRODUCTION

Past studies have concentrated on unlocking scientific secrets of lunar soil. Extracts of scientific studies on chemistry and petrography of the 163 individual soils and an extensive bibliography are found in *Handbook of Lunar Soils* (Morris *et al.*, 1983). A review of lunar soil petrography is given by Heiken (1975). Although lunar soil chemistry is fairly well known, engineering properties and industrial reactions are not as well studied.

Mechanics and thermal information on *in situ* soil conditions was gathered by early researchers from television, surface photography, and measurements using a penetrometer and heat flow probe. Observations on the lunar surface include the Apollo lunar module descent engine blowing dust, depths of footprints on crater rims, the rover throwing dirt in the "grand prix," drilling, trenching, scooping, and raking. *In situ* properties are most relevant to the use of lunar soil for tunneling, heaping, and excavating, and as a substrate for buildings and vehicles. The properties of interest are the *in situ* bulk density and porosity. For surface activities similar to those conducted on the Apollo missions, these properties are probably known well enough.

Other properties, intrinsic to the soil grains, become important for those experiments where lunar soil is an active ingredient in a process. These properties include composition, rock form (crystalline, glassy), grain size, grain shape, grain strength, grain surface reactivity, dielectric constant, and magnetic susceptibility. Present interest includes experiments for extracting oxygen from the soil, melting or chemically reacting the soil for use as structural material, and growing organisms on the soil.

BRIEF DESCRIPTION OF LUNAR SOIL

Lunar soil can be described in familiar terrestrial terms as well-graded silty sands or sandy silts with an average particle size by weight between 0.040 and 0.130 mm (Carrier *et al.,* 1973). The density of *in situ* bulk lunar soil, as determined from large diameter core tube samples, is typically 1.4 to 1.9 g/cm^3. The bulk density increases with depth, and below 10-20 cm the soil is often at higher density than is required to support the overburden in lunar gravity (Carrier *et al.*, 1973). Spheres, angular shards, and fragile, reentrant, vesicular grains are among the diverse shapes found in most lunar soils. The most abundant particles composing the soil are igneous or breccia lithic grains, mineral grains, glass fragments, and the unique lunar agglutinates. Major lunar minerals are pyroxenes, anorthite, ilmenite, and olivine. Compositionally, the lunar soils fall into two broad groups: the highlands soils, which developed on anorthositic bedrock, and the mare soils, which developed on basaltic bedrock. The mare soils can be further subclassified as to high or low titanium content. Highlands soils are relatively enriched in aluminum and calcium, while mare soils are relatively enriched in iron, magnesium, and titanium. Average major element chemistry of these three types is given in Table 1.

Table 1. Major Element Chemical Composition of Lunar Soils and Soil Simulants

	Lunar Highlands Soils* (%)	Lunar Low Titanium Mare Soils† (%)	Lunar High Titanium Mare Soils§ (%)	Hawaiian Basalt** (%)	High Titanium Mare Simulant‡ (%)
SiO_2	45.0	46.4	42.0	46.4	41.7
TiO_2	0.5	2.7	7.5	2.4	7.5
Al_2O_3	27.2	13.5	13.9	14.2	12.8
Fe_2O_3	-	-	-	4.1	3.7
FeO	5.2	15.5	15.7	8.9	12.8
MgO	5.7	9.7	7.9	9.5	8.5
CaO	15.7	10.5	12.0	10.3	9.2
Total	99.3	98.3	99.0	95.8	96.2

*Average composition of Apollo 16 soils compiled from *Handbook of Lunar Soils* (Morris, 1983).
†Average composition of Apollo 12 soils from Taylor (1975), p. 62.
§Average composition of Apollo 11 soils from Taylor (1975), p. 62.
**Composition of Hawaiian basalt HAW-11 from *Basaltic Volcanism on the Terrestrial Planets,* p. 166.
‡Calculated composition from recipe in Table 2. Iron in ilmenite as FeO.

CHANGES IN SOIL FROM MOON TO LABORATORY

Soil cannot be removed from the surface of the Moon without altering at least some of the *in situ* characteristics such as bulk density and stratigraphy. The least physically disturbing way of sampling the lunar soil was with the large diameter core tubes used

Table 2. Changes in Soil from Moon to Lab

	Conditions	Changes
Moon	Impact-derived particle packing High vacuum	
Curatorial Facility	Dry nitrogen	Loss of original packing Adsorb water (minor)
Laboratory	Laboratory atmosphere	Adsorb water (major) Oxidation

on Apollo 15, 16, and 17 (Carrier *et al.*, 1971). Soil undergoes still further changes in the experimenter's laboratory (Table 2). On the lunar surface soil particles reside in a hard vacuum, free of water molecules and other atmospheric gases. The packing of particles is affected by continual meteorite bombardment. The dominant effect of this pounding is to pack the soil more tightly, although occasionally soil particles on the surface are ejected and then settle to a less dense configuration on crater rims (Carrier, 1973).

In the lunar sample curatorial facility, "pristine" samples are stored and handled only under dry nitrogen. Even so, small amounts of water and other gases are probably adsorbed on the highly reactive surfaces of lunar soil grains. The soil grains have lost their original packing during excavation, transit to Earth, and laboratory handling.

Furthermore, the ambient atmosphere of the experimenter's laboratory, with its relatively high water vapor and oxygen content, causes much more water to be adsorbed on the grain surfaces and some oxidation to occur. For example, the abundant metallic iron in lunar soil rusts easily.

SOME CRITICAL DIFFERENCES BETWEEN SIMULANTS AND LUNAR SOIL

Solar radiation and meteorite impacts, large and small, alter soil grains in ways that are difficult to duplicate on Earth. Also, lunar minerals are compositionally different, on a minor scale, due to the lack of volatile elements and reduced amounts of oxygen when the minerals were formed. Some of these unique lunar characteristics can be reproduced in very small quantities of simulant in experimental guns, charged particle beams, or furnaces. However, it is not practical to make usable quantities of simulants by these methods. Since simulants will probably be made using crushed, naturally-occurring minerals, they will be different from true lunar soil in several ways (Table 3).

Agglutinates, Iron Metal

Since the Moon has no atmosphere, very small meteorites impact the soil at high velocity, melting and shocking the rocky soil grains. Evidence of an impact on a 1 mm

Table 3. How Successful is a Simulant?

Can Simulate	Difficult to Simulate
Grain size distribution	Agglutinate glass with dispersed metal, grain shape
Gross mineral composition	Solar wind nuclei implantation Shock effects (grain strength)
General chemical composition	Mineral chemistry (reduced elements, no hydration)

diameter glass sphere taken from lunar soil is shown in Fig. 1. The splatters of glass from many repetitions of such micrometeorite impacts can glue tiny grains together in convoluted structures called agglutinates (Fig. 2). Iron metal blebs of 10 nm diameter are distributed throughout the agglutinatic glass, making the glass magnetic. Agglutinates can make up over 50% of a mature lunar soil. This gluing together of smaller grains into larger ones is part of two competing processes, for impacts also break down soil grains into smaller ones.

Solar Wind

Because the Moon does not have a global magnetic field, high velocity nuclei from the solar wind impinge directly on small soil grains. These nuclei, of which hydrogen and helium are the most common, become implanted in the outer few angstroms of soil grains, creating an amorphous layer. In mature soils this solar wind hydrogen can exceed 100 ppm.

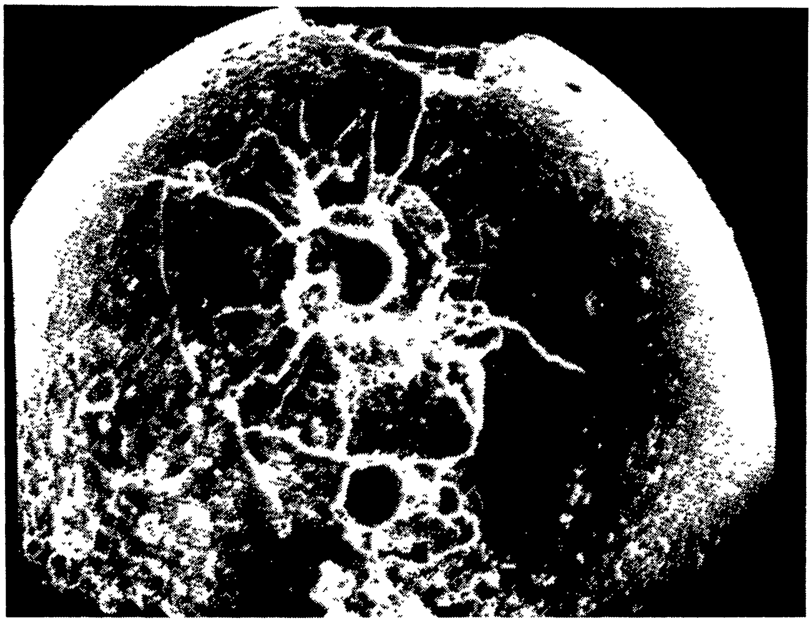

Figure 1. One millimeter diameter lunar glass sphere with micrometeorite impact pit. Photo courtesy of D. S. McKay (S-71-48106).

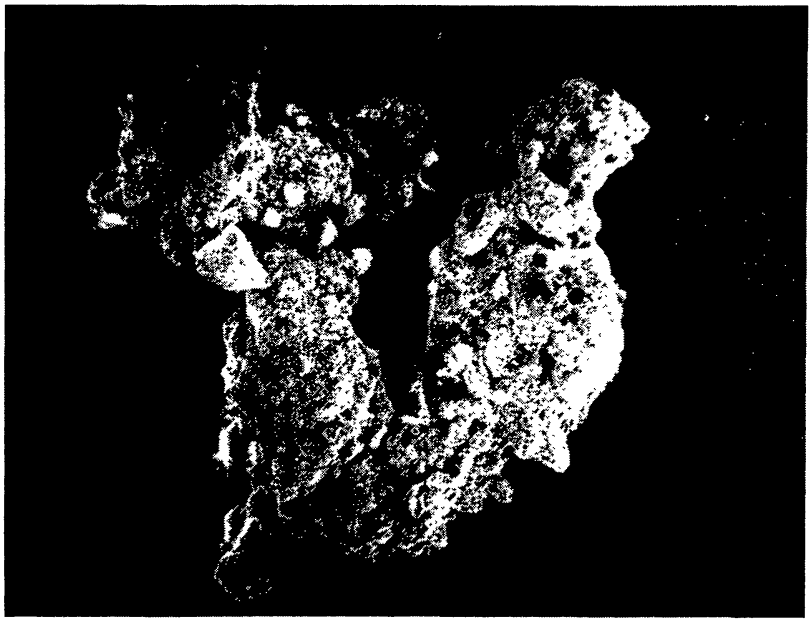

Figure 2. One millimeter diameter agglutinate. Photo courtesy of D. S. McKay (S-71-24575).

Shock Effects

The shock effects of meteorite impacts are commonly retained in lunar soil grains. Impacts fracture and weaken the mineral grains found in the lunar soil.

Mineral Chemistry

The major lunar minerals (anorthite, pyroxene, ilmenite, olivine) are similar in gross aspects to their terrestrial counterparts. However, the lunar minerals do not contain bound water in the crystal structure and have not been altered by hydration reactions on grain boundaries. Due to extremely low oxygen fugacities at the time of crystallization, several elements in lunar minerals are found in a more reduced state. Combined iron is almost totally ferrous iron, and iron metal may be found in interstitial phases and dispersed in glass. Titanium and chromium occur in the more reduced valence states of +3 and +2, respectively. Lunar ilmenite does not contain hematite as many terrestrial ilmenites do.

LUNAR FINES AS EXPERIMENTAL SAMPLES

Lunar samples are allocated very sparingly, and investigators are encouraged to work on the smallest possible samples. For example, scientific investigators typically determine major element chemistry from only 50 mg of material. Since engineering and industrial studies often require much larger sample size, experimenters must, when possible, scale down their experiments and make use of simulants.

Any lunar samples that may be available for technology studies will probably come from the residue of fines left in the Apollo collection bags. Early missions collected fewer, but larger, soil samples, On later missions, samples were smaller, more carefully chosen to sample different phenomena, and placed in individual bags.

Table 4. Grams of Sample Bag Residues from Apollo Missions

Apollo 11	55 g
Apollo 12	-
Apollo 14	225 g
Apollo 15	335 g
Apollo 16	1808 g
Apollo 17	3525 g
Total	5948 g

The residue of fine material remaining in the rock and soil sample bags (about 5 kg total) could be pooled and homogenized for each mission except Apollo 12 (Table 4). This would result in a mixture of fines, representing an average chemical composition for each site of large enough size to serve as a standardized sample. However, these samples would not be representative of a true soil since rock dust would be admixed. Soil maturity (degree of exposure to micrometeorites and solar wind), as determined by fine-grained metallic iron content (Morris, 1978), would give a general indication of proportion of soil to rock dust. Investigators concerned with agglutinate, metal, and solar wind content could then make adjustments for under-representation of these components in the pooled fines.

As a standard sample, these pooled fines would be of known composition, grain size distribution, and maturity. This would be advantageous for comparisons among experiments. Use of these bag residues would be an efficient use of the Apollo collection, since their mixed origin makes them less valuable scientifically.

SIMULANTS FOR EXPERIMENTS

Since the properties to be simulated and degree of fidelity required are different for laboratory experimentation than for testing equipment and structures, simulants for these two uses are discussed separately. In general, simulants for laboratory experimentation require greater fidelity to chemical and mineral composition, in addition to grain size distribution. In creating simulants, costs must be weighed against benefits of increasing fidelity to lunar soil. The approach described below is a "middle-of-the-road" effort, when compared to the low cost extreme of using the nearest sand or crushed rock and the high cost extreme of creating micrometeorite impacts and solar wind implantations one by one in experimental guns and ion beams. Simulating the lunar soil for laboratory experimentation is approached from three aspects: soil grain size distribution, soil particle type distribution, and particle chemistry.

Grain Size Distribution

Grain size distribution curves have been compiled that encompass most Apollo soils (Carrier *et al.*, 1973). The grain size distribution of simulants should be created with the fewest sieve sizes that adequately characterize the grain size distribution curve and yet are practical to use. Thus, simulant composition should be defined as 90% finer than

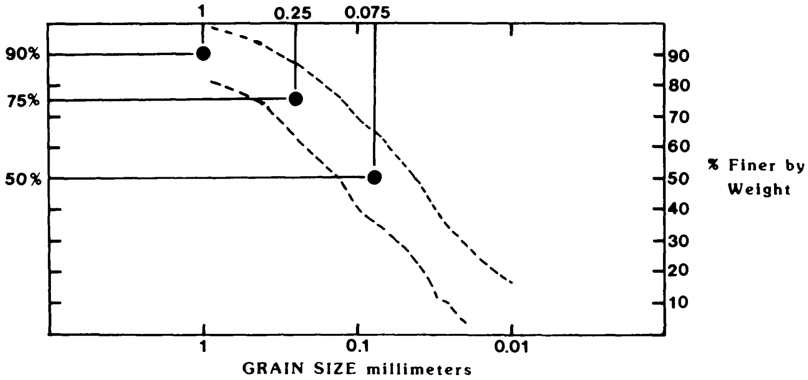

Figure 3. Grain size distribution curves encompassing most Apollo soils. Plot and data adapted from Carrier et al. (1973). Percent finer by weight at sieve sizes 1.0, 0.25, and 0.075 mm are used to define simulant characteristics.

1 mm, 75% finer than 0.250 mm, and 50% finer than 0.075 mm (Fig. 3). The distribution curve is not precisely simulated below 0.075 mm, because it is impractical to sieve large volumes of rock below this limit. Therefore, it is important to calibrate the pulverizing process in the small size range.

Particle Type Distribution

Nearly all particles comprising the lunar soil are lithic (chiefly breccia and poikilitic rocks in the highlands and breccia and basalt in the maria), mineral or glass fragments or agglutinates. The simulation is simplified by using crushed basalt or minerals to substitute for the lithic and mineral fragments and by using crushed glass to substitute for glass fragments and agglutinates. Although lunar particle type distribution varies with maturity of the soil, source rock type, and particle size, both mature highlands and mature mare soils can be approximated with a mineral or rock to glass ratio of 1:1 for sieve fraction <0.250 mm and a ratio of 3:1 for sieve fraction >0.250 mm. [These proportions were calculated from data for sample 60010 given in McKay *et al.* (1977) and from data for sample 71016 given in Heiken and McKay (1974).]

A Highlands Simulant

The target chemical composition for the highlands simulant is the average of Apollo 16 soils as given in Table 1. Normative calculations (Chayes and Metais, 1964), based only on Si, Al, Fe, Mg, and Ca indicate that a 3:1 weight ratio of anorthite ($CaAl_2Si_2O_8$) to pyroxenes (of mixed composition) would approximate this chemical composition. Adding pyroxenes raises both the iron and magnesium content.

Unaltered anorthite is not common on Earth. The least altered anorthite crystals can be found associated with frothy glass near some andesitic volcanoes, such as Miakejima near Tokyo. Anorthite also is found mixed with other minerals in andesitic areas and as anorthosite rock in layered intrusions, of which the Stillwater complex in Montana is an example.

The orthopyroxene bronzite is a close practical substitute for the norm-calculated pyroxene ratios of hypersthene (orthopyroxene) to diopside (clinopyroxene) of 6:1.

Glass of the highlands composition given in Table 1 can be made by Corning Glass Company by the dri-gauge method (Minkin *et al.*, 1976).

In summary, a highlands simulant can be made by combining crushed anorthite, pyroxene, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

A High Titanium Mare Simulant

The target chemical composition for the high titanium mare simulant is the Apollo 11 soil average given in Table 1. The lithic and mineral component can be approximated by terrestrial basalts plus ilmenite. HAW-11 (Basaltic Volcanism Study Project, 1981), whose chemical composition is also given in Table 1, is an example of a suitable basalt. Combining this basalt with ilmenite ($FeTiO_3$) in a 9:1 proportion raises the titanium content of the mixture to that of the Apollo 11 soil. The resulting mixture also improves the calculated fit to Si, Fe, and Mg percentages of the Apollo soil (Table 1).

Glass of high titanium mare composition can also be made from melting oxides. Naturally occurring, basaltic-composition volcanic glass, such as is found in Hawaii could be used, but probably will not have a titanium concentration as great as the high titanium mare soils.

In summary, a high titanium mare simulant can be made by combining crushed Hawaiian basalt HAW-11, ilmenite, and synthetic glass in proportions based on grain size, lithic or glassy character, and chemistry. A sample recipe of this type is given in Table 5.

SIMULANTS FOR TESTING EQUIPMENT AND STRUCTURES

Important parameters to simulate for testing equipment and structures include bulk density and porosity. Grains of correct size distribution and specific gravity are needed,

Table 5. Recipes for Lunar Soil Simulants

	Sample Highlands Simulant: Anorthite to Pyroxene Ratio 3:1*			
	<0.075 mm	0.075 to 0.25 mm	0.25 to 1.0 mm	>1.0 mm
Anorthite	18.8	9.4	8.4	5.6
Pyroxene	6.2	3.1	2.8	1.9
Glass	25.0	12.5	3.8	2.5
	Sample High Titanium Mare Simulant: Basalt to Ilmenite Ratio 9:1*			
	<0.075 mm	0.075 to 0.25 mm	0.25 to 1.0 mm	>1.0 mm
Basalt	22.5	11.3	10.1	6.8
Ilmenite	2.5	1.2	1.1	0.7
Glass	25.0	12.5	3.8	2.5

*To make 100 g of simulant, mix components by grams indicated in table.

The same grain size fractions and lithic to glass ratios were used for both simulants: >1 mm =0.10; 0.25–1 mm =0.15; 0.075–0.25 mm =0.25; <0.075 mm =0.50 (total = 1.00). The lithic to glass ratio for >0.25 mm =3:1 and for <0.25 mm =1:1.

so chemistry and mineralogy are less important. Also, since much larger quantities of simulant are needed (tons), crushing and grinding of a single component, usually basalt, on commercial size equipment would be used. Nearly 2500 kg of a basalt simulant was fabricated and characterized for testing the lunar rover (Mitchell and Houston, 1970; Green and Melzer, 1971). Crushed basalt also has been used for lunar resource utilization studies (Steurer, 1982).

The importance of packing the simulant properly after grinding is illustrated in the testing of the Apollo lunar surface drill by Martin Marietta. The simulant, used during design of the drill, was packed to a lesser density than was actually encountered on Apollo 15. The surprisingly dense soil at Hadley Rille made the drilling effort more difficult than expected. The density of the entire Apollo 15 drill sample was 1.75 g/cm^3, but the deepest section was 1.93 g/cm^3 (Carrier, 1974). Therefore, in preparation for subsequent drill testing, engineers recompacted the simulant to the densities encountered at Hadley Rille. The difficult task of achieving this high density for crushed vesicular glass and lithic particles was accomplished using electric tampers to compress each shallow layer (3–6 inches thick) as it was added to the test bed (Britton, personal communication, 1985).

CONCLUSIONS

When planning experiments for activities to take place on the Moon, investigators should remember the following.

1. Lunar soil in the laboratory does not accurately represent lunar *in situ* conditions. The Apollo soils have lost their original particle packing and have adsorbed volatiles.
2. Simulants can be made by ordinary means that reproduce specific properties of lunar soil such as grain size distribution, gross mineral composition, or general chemical composition.
3. Certain lunar soil characteristics are difficult to duplicate in simulants. These include agglutinates with their convoluted shapes and iron metal, implanted solar wind nuclei, impact shock effects on grains, and minerals with reduced elements.
4. A very small amount of lunar soil will be available for experimentation. Investigators should scale down their experiments and use simulant whenever possible.

Acknowledgments. This paper was substantially improved through suggestions given by the following thoughtful reviewers: D. P. Blanchard, D. S. McKay, W. W. Mendell, and R. J. Williams. Their comments are much appreciated. This work was supported by contract NAS-9-15425.

REFERENCES

Basaltic Volcanism Study Project (1981) *Basaltic Volcanism on the Terrestrial Planets.* Pergamon, New York. 1286 pp.

Carrier W. D. III (1973) The relative density of lunar soil. *Proc. Lunar Sci. Conf. 4th,* pp. 2403–2411.

Carrier W. D. III (1974) Apollo drill core depth relationships. *Moon, 10,* 183–194.

Carrier W. D. III, Johnson S. W., Werner R. A., and Schmidt R. (1971) Disturbance in Samples recovered with the Apollo core tubes. *Proc. Lunar Sci. Conf. 2nd,* pp. 1959–1972.

Carrier W. D. III, Mitchell J. K., and Mahmood A. (1973) The nature of lunar soil. *J. Soil Mech. Found. Div.*, American Society of Civil Engineers, 99, 813-832.

Chayes F. and Metais D. (1964) On the relationship between suites of CIPW and Barth-Niggli Norms. *Carnegie Inst. Washington, Year Book 63*, 193-195.

Green A. J. and Melzer K. J. (1971) *Performance of Boeing LRV Wheels in a Lunar Soil Simulant. Rep. 1, Effect of Wheel Design and Soil.* Tech. Rep. M-71-10, U.S. Army Engineer Waterways Experiment Station, Vicksburg. 83 pp.

Heiken G. (1975) Petrology of lunar soils. *Rev. Geophys. Space Phys., 13*, 567-587.

Heiken G. and McKay D. S. (1974) Petrography of Apollo 17 soils. *Proc. Lunar Sci. Conf. 5th*, pp. 843-860.

McKay D. S., Dungan M. A., Morris R. V., and Fruland R. M. (1977) Grain size, petrographic, and FMR studies of the double core 60009/10: A study of soil evolution. *Proc. Lunar Sci. Conf. 8th*, pp. 2929-2952.

Minkin J. A., Chao E. C. T., Christian R. P., Harris E. E., and Norton D. R. (1976) Three synthetic lunar glasses. *Meteoritics, 11*, 167-171.

Mitchell J. K. and Houston W. N. (1970) Mechanics and stabilization of lunar soils. In *Lunar Surface Engineering Properties Experiment Definition*, Final Report: Vol. 1 of 4, Space Sciences Laboratory Series 11, Issue 10. University of California, Berkeley. 166 pp.

Morris R. V. (1978) The surface exposure (maturity) of lunar soils: Some concepts and I_S/FeO compilation. *Proc. Lunar Planet. Sci. Conf. 9th*, pp. 2287-2297.

Morris R. V., Score R., Dardano C., Heiken G. (1983) *Handbook of Lunar Soils.* NASA Planetary Materials Branch Publication No. 67, NASA/Johnson Space Center, Houston. 913 pp.

Steurer W. H. (1982) *Extraterrestrial Materials Processing.* JPL Publication 82-41, pp. 27-39. Jet Propulsion Laboratory, Pasadena.

Taylor S. R. (1975) *Lunar Science: A Post Apollo View.* Pergamon, New York. 372 pp.