scopic curves for other parts of the moon can be expected to yield information on areal differences in mineralogy and in glass content.

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Apollo 11 Soil Mechanics Investigation

Abstract. *The fine-grained surface material at the Apollo 11 landing site is a brownish, medium-gray, slightly cohesive granular soil, with bulky grains in the silt-to-fine-sand range, having a specific gravity of 3.1 and exhibiting adhesive characteristics. Within the upper few centimeters, the lunar soil has an average density of about 1.6 grams per cubic centimeter and is similar in appearance and behavior to the soils studied at the Surveyor equatorial landing sites. Although considerably different in composition and in range of particle shapes, it is similar in its mechanical behavior to terrestrial soils of the same grain size distribution.*

The upper few centimeters of surface material in the vicinity of Tranquillity Base consist of a brownish, medium-gray, slightly cohesive granular soil largely composed of bulky grains in the silt-to-fine sand size range. Angular-to-subrounded rock fragments ranging up to 1 m in size are distributed throughout the area. Some of these fragments are lying on the surface, some are partly buried, and others are barely exposed.

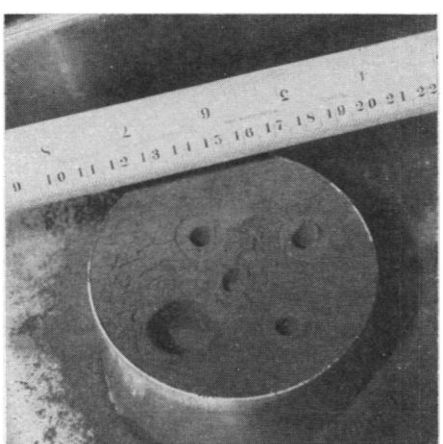


Fig. 1. Penetration of loosely placed lunar soil sample at the nitrogen cabinets of the LRL Biological Preparation Laboratory. [LRL photo S-69-47484]

The soil grains vary in shape from blocky angular with smooth plane surfaces to completely spherical; some of the larger particles are vesicular. No shards, needles, or filaments have been observed. A large portion of the soil grains consists primarily of glasses, with chemical composition covering a wide range. The color of these particles varies from clear, to dark reddish-brown, to dark gray.

The grain size distribution of fine-grained material collected with the documented sample, the core tubes, and the bulk sample was found, in all cases, to be that of a silty fine sand. However, aggregation of individual particles may have biased the analyses toward the large size range.

The following observations and measurements were made (*1*, *2*) on lunar soil samples placed in the nitrogen cabinets of the Lunar Receiving Laboratory's Biological Preparation Laboratory at room temperature and at normal atmospheric pressure.

1) Visual examination of core-tube soil samples 10004 and 10005 revealed that the soil was remarkably uniform in color and texture; fine reflecting surfaces over about 10 percent of the area produced a sparkling appearance. There was no variation in structure with length along the samples, although there was a very slight color difference between the upper and lower halves of sample 10004; however, probing indicated no discernible differences in mechanical properties. Sample 10005 contained numerous small cracks and voids. Its average bulk density, not taking into account the voids and cracks, was about 1.66 g/cm^3, as compared with 1.54 g/cm^3 for sample 10004.

2) The specific gravity of the soil in the core tubes was found to be 3.1, as measured by a gas comparison pycnometer. This is considerably higher than the typical value of 2.7 for terrestrial soils and may be attributable to the fact that the lunar soil is composed mainly of the basic igneous minerals (for example, plagioclase, olivine, and pyroxene), as well as relatively large amounts of titanium and iron oxides.

3) On the basis of the specific gravity and bulk-density measurements, the void ratios of the core-tube samples were found to be 1.01 and 0.87. The respective porosities are 50.1 and 46.5 percent. It should be noted that the core bit of both core samplers was flared inward at 15°, the reverse of the direction for most terrestrial samplers. Thus, the soil was probably deformed considerably during sampling, and the measured bulk densities and porosities may not necessarily be indicative of the bulk density and porosity of the undisturbed lunar soil.

4) The bulk density of bulk sample material finer than 1 mm, placed as loosely as possible in a container, was determined to be 1.36 g/cm^3, corresponding to a void ratio of 1.28 and a porosity of 56 percent. Under the 1/6-*g* lunar gravity, the adhesive forces between the particles would probably

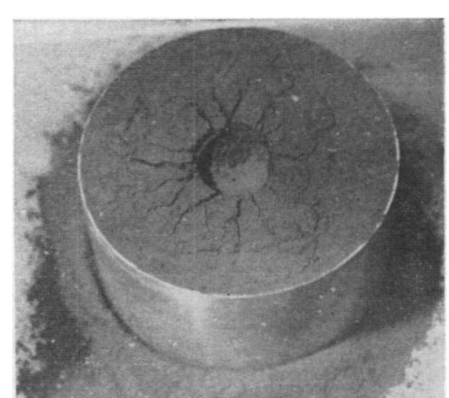


Fig. 2. Penetration of compacted lunar soil sample at the nitrogen cabinets of the LRL Biological Preparation Laboratory. [LRL photo S-69-47489]

Table 1. Results of lunar soil bulk sample penetration test.

Test	Density (g/cm^3)	Force (lb)	Area ($in.^2$)	Pressure ($lb/in.^2$)	Pene-tration (in.)	Pressure/penetration ratio (lb $in.^{-2}$ $in.^{-1}$)
1	1.36	< .41*	0.049	< 8.3	0.25	
2	1.36	< .41*	.049	< 8.3	.77	
3	1.36	< .41*	.049	< 8.3	.77	
4	1.36	< .41*	.049	< 8.3	.77	
5	1.36	.69	.416	1.65	.79	2.1
6	1.77	.41	.049	8.3	.32	25.9
7	1.77	1.22	.049	24.8	.67	37.0
8	1.77	< .41*	.049	< 8.3	.25	
9	1.77	2.20	.049	44.7	1.00	44.7
10	1.77	1.30	.049	26.5	.83	31.9
11	1.77	8.70	.416	20.7	.67	30.9
12a	1.80	6.50	.416	15.6	.26†	60.9
12b	1.80	17.95	.416	43.1	.77†	84.5

* Penetrometer did not meet with sufficient resistance to compress the spring. Tabulated force is weight of penetrometer. † Penetrometer was removed after achieving pressure of 15.6 $lb/in.^2$ at a penetration of 0.26 inch; it was applied again at the same place and pushed into the soil until the applied unit load reached the value 43.1 $lb/in.^2$ at a penetration of 0.77 inch from the original surface of the sample.

permit a looser soil structure to develop. In a second test series, the soil was compacted in several layers by rodding, tamping, and compressing to a maximum bulk density of 1.80 g/cm^3, corresponding to a void ratio of 0.72 and a porosity of 41.8 percent. In each compaction state the resistance to penetration of the soil sample was measured by means of a small, spring-loaded penetrometer. Results of these tests are shown in Table 1. In the loose state the soil failed in a punching mode, as shown in Fig. 1; in the dense state the failure mode, shown in Fig. 2, indicated classical incompressible shear failure.

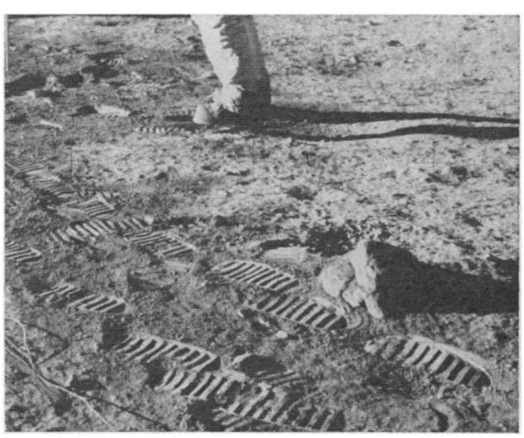
The physical characteristics and mechanical behavior of the lunar soil as deduced from extravehicular activity data can be summarized as follows (*1*, *2*).

1) The loose, powdery, surficial fine-grained material ranging up to fine-sand size tended to adhere to any object with which it came into contact. Fine, powdery material adhered to lunar rock samples brought back to earth, and left a trace of fine dust coating the core tubes that were returned to the Lunar Receiving Laboratory. This adhesion, however, was not of sufficient magnitude to offer any resistance to pulling of staffs inserted into the lunar surface.

2) The lunar surface is relatively soft to depths ranging between 5 and 20 cm. It can be easily scooped, offers low resistance to penetration, and provides low lateral support for staffs, poles, or core tubes. Beneath this relatively soft surface, the penetration resistance of the material increases considerably.

Results of tests made at the LRL to study penetration resistance of the lunar soil (Table 1) indicate that, within the bulk-density range of 1.36 to 1.80 g/cm^3, the resistance to penetration increases by a factor of 20. Therefore, if the lunar soil at the Apollo 11 landing site is compacted to a density somewhat greater than the minimum, it should offer sufficient static resistance per inch of penetration, estimated at 3 $lb/in.^2$ per inch (*2*, *3*), to account for the behavior observed by the astronauts when they pushed various tools into the surface, without postulation of the presence of an overconsolidated layer, a cemented layer, or bedrock. It does not follow, however, that no such layer existed at any or all of the locations where various penetrators were inserted into the lunar surface during extravehicular activity.

3) Most of the astronauts' footprints caused compression of the lunar surface soil, although in some instances, bulging and cracking of soil adjacent to a footprint occurred. The latter observation indicates shearing rather than



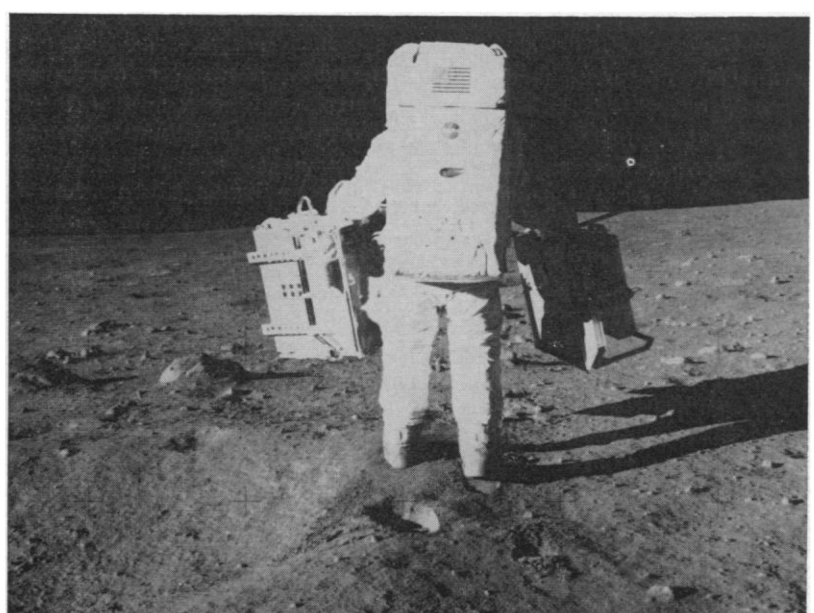


Fig. 3 (above). Typical astronaut footprints on relatively level lunar surface in the vicinity of the flagpole. [NASA AS 11-40-5874] Fig. 4 (right). Typical astronaut footprints at the top edge of a soft-rimmed crater. Combined weight of astronaut and Early Apollo Scientific Experiments Package produced a unit bearing pressure of 1.4 $lb/in.^2$ on one boot area in the lunar gravity field. [NASA AS 11-40-5946] compressional deformation of the soil.

4) The soil possesses a small but finite amount of cohesion, evidenced by the following observations: (i) fine grains stick together, and sometimes soil clumps (about 10 percent of the blocky material protruding above the surface) could not be distinguished from rock fragments; (ii) natural clods of fine-grained soil crumbled under the astronauts' boots, indicating some cementation between the grains, although, in LRL tests, soil grains were found to cohere again to some extent after being separated; (iii) initially loose and fluffy material readily compacted under load and retained the detail of a deformed shape (Fig. 3), thus enhancing the astronauts' mobility on previously traversed surfaces; (iv) the material could stand unsupported on vertical slopes at least a few inches high; (v) during the bulk-sample collection, it was observed that, as the scoop cut through the lunar soil, the remaining material left a sharp solid edge, but the material that went into the scoop crumbled with no evidence of particle aggregation; (vi) the holes made by the core tubes appeared to remain intact upon the removal of the tubes; (vii) there was no tendency for the material collected in the core tubes to pour out, and the material was similar in appearance to a terrestrial moist soil; and (viii) during the terminal stages of the lunar module landing, the height at which soil erosion caused by exhaust from the spacecraft engine first became noticeable was approximately 100 feet, indicating that even the loose, powdery, top surficial layer of lunar soil possesses some cohesion, although possibly of lower magnitude than that exhibited by the underlying material, because cohesionless soil of the same grain-size range would be moved at a much higher elevation.

5) Confinement of the loose surface material leads to a significant increase in resistance to deformation, which is characteristic of soils deriving a large portion of their strength from interparticle friction. The relevant material properties can be assessed from the following observations. (i) Available information indicates that the lunar module landing was achieved under essentially static conditions as far as the landing gear was concerned and the relatively small penetrations (1 to 3 inches) of the lunar module footpad correspond to static bearing pressures exerted by the footpads on the lunar surface in the range of 2.1 to 0.8 lb/in^2. (ii) The relatively small depth of typical astronaut footprints, shown in Fig. 3, was about ½ inch when the static bearing pressure exerted by the astronaut weight on one boot was about 1 lb/in^2. (iii) Soft spots encountered during the extravehicular activity were generally located at the rims of small, fresh craters which consisted of loose, very-fine-grained material with essentially no large rock fragments. Close to the rim and especially on the upper edge of inside slopes, where the material was loose and relatively unconfined, the astronauts sank as much as 6 to 8 inches, as may be seen in Fig. 4.

In all of the above cases, calculations (*2*) based on the Terzaghi equation for ultimate bearing capacity (*4*), with appropriate adjustments to account for circular contact areas, as in the case of the lunar module footpads, and for sloping ground (*5*), as in the case of the soft-rimmed craters, indicate the following.

1) For a Surveyor soil model (*6*) with a density of 1.5 g/cm^3, a cohesion ranging between 0.05 and 0.1 $lb/in.^2$, and a friction angle of 35°, the assumed soil properties account reasonably well for the observed behavior.

2) Because of the small lunar gravity, the relatively small critical dimension of loaded areas, the shallow subsurface depth at which the loads were applied, and the fact that the lunar soil is predominantly frictional, it appears that the cohesion of the lunar soil, though slight, is a key characteristic contributing to the bility of the soil to support bearing loads.

Various observations and measurements at the LRL indicate that the cohesion of the lunar soil is not affected by short-term exposure to nitrogen atmosphere. (i) The core-tube samples retained their cylindrical shape upon removal of the top halves of the inner split-tube liners, and disturbance revealed that cohesion was small but sufficient to hold small clumps of fine particles together. (ii) Numerous cracks and voids, developed in the core samples as a result of disturbance, were retained. (iii) During sieving, very fine particles tended to form, break, and reform into lumps when shaken, as though the soil were slightly damp. (iv) When material finer than 1 mm was being scooped from the bulk sample container, the scoop cut clean, smooth vertical walls approximately 3 inches deep, in the soil mass, similar to the trenches dug in the lunar surface by the surface samplers of Surveyors III and VII (*6*). (v) Using bearing-capacity analysis and penetration-resistance test data from the test performed on the maximum-density soil (Table 1; Fig. 2), the cohesion of the lunar soil sample was estimated to vary between 0.20 and 0.05 $lb/in.^2$, values corresponding to angles of internal friction of the soil ranging between 35° and 45°. These strength parameters are in the range deduced from Surveyor data analyses (*6*) and are in reasonable agreement with results from shear strength tests performed on simulated lunar soils having the same grain-size distribution and compacted to the same void ratio as the lunar soil sample (*3, 7*).

The nature of the cohesion of the lunar soil in place requires more detailed investigation. Although the various observations and measurements suggest that it may not be affected by short-term exposure of the soil in nitrogen atmosphere, it has appeared to degrade after a few weeks of storage. Information on the actual pressure and composition of the lunar atmosphere, or on any outgassing from the interior of the moon occurring at the lunar surface, may shed new light on the mechanisms and processes governing this important mechanical property of lunar soil.

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