Physical and mechanical properties of lunar soil

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Resume

The purpose of this paper is to systematise and review the series of investigation concerning the physical and mechanical properties of the soil on the Moon. The results of these investigations permit a deeper understanding of the soil-forming processes of the uppermost layers on the Moon and on the other planets. They are also needed to clarify general trends and to provide basic data and engineering models in order to develop new techniques for planetary exploration. This seems to be of vital importance nowadays, because we are on the eve of a new stage in the development of missions to the Moon and the investigation of other planets.

Introduction

The knowledge of the physical and mechanical properties of the soil is of fundamental importance because it is the basic for engineering activity aimed at construction of lunar bases and for mineral resource exploration. During manned flights the astronauts are operating and walking along the surface and knowledge about surface properties determines considerably the safety of the entire mission. Therefore, for further investigation and exploration of the Moon and on the other planets it is vital to know the physical and mechanical properties of the soil and it is evident that such studies should proceed in advance to avoid unnecessary risk and expenditure of certain missions. The first task is to study thoroughly the data accumulated and to outline the methods for their solution (Gromov, 1999).

1. Basic studies of the physical and mechanical properties of lunar soil

The study of the physical and mechanical properties of lunar soil had been started even before the first flights to the Moon were realised. The surveys were mainly based on the results of radio-telescopic investigation of the lunar surface as well as on studies of terrestrial soils and artificial materials with the same optical, thermal, and electrical characteristics as the lunar soil. Those data served as the basis for designing unmanned lunar spacecraft (Krotikov and Troitsky, 1963).

A new step in the study of lunar soil occurred with the landing of unmanned spacecrafts on the lunar surface. The information acquired during these missions provided us with a true picture of the properties of lunar soil. Based on those experiments, new models of lunar soil were developed, and also closest analogues of terrestrial soil were selected. Fresh igneous deposits in the vicinity of intensive volcanic activity proved to be quite good terrestrial simulates of lunar soil (Cherkasov et al., 1967).

No less important step in the study of lunar soil was the delivery of soil samples to Earth, followed by their detailed and comprehensive investigation in terrestrial laboratories.

A large number of studies on physical and mechanical properties of lunar soil were also performed by means of unmanned vehicles Lunokhod-1 and Lunokhod-2 and by "Apollo" astronauts. The investigation of lunar soil was carried out at landing sites which appear to be geomorphologically typical for the lunar surface.

Studies of physical and mechanical properties of lunar soil were grouped as follows:

1. Testing of returned lunar soil samples in order to reveal the main trends and relation of the physical and mechanical properties with respect to the bulk density (Gromov *et al.,* 1971, Carrier *et al.*, 1973, Leonovich *et al.*, 1975, Kemurdjian *et al.*, 1976, Gromov *et al.*, 1979);
2. Studying the physical and mechanical properties of lunar soil under in situ conditions and correlating with the geomorphological environments conditions (Bazilevsky *et al.,* 1984, Carrier *et al.,* 1991, Kemurdjian *et al.,* 1976, Gromov *et al.,* 1986, Kemurdjian *et al.,* 1993);

3 Selecting and studying terrestrial analogues of lunar soil for conducting tests on the Earth (Krotikov *et al.,* 1963, Cherkasov *et al.,* 1975, Gromov *et al.,* 1992).

2. Lunar soil granulometric composition

One of the main soil characteristics that governs its physical and mechanical properties is the granulometric composition (i.e., size and shape of the particles). Particle-size distribution of the soil samples delivered to the Earth was defined by dispersion, by conductometric method and by microphotography (Stacheev, 1979). The general conclusion is that the particle-size distributions are relatively uniform, even though the samples were taken from different regions of the lunar surface. The samples, for the most part, consist of small mineral particles that differ in shape. The particles easily stick to each other to form separate clods and aggregates. In its granulometric composition, lunar soil resembles dusty sand.

In the papers of Carrier (1973) and Stacheev (1979), data concerning lunar soil samples granulometric composition are cited. These data allow to come to the following general conclusions:

a) the granulometric composition of the lunar soil samples taken from the different regions of the Moon is sufficiently well submitted to the logarithmic - normal law of particle size distribution depending on particle relative contents by weight in soil;

b) the average particle size and particle size standard deviation values expressed in logarithmic units are well correlated and standard deviation increases with the average particle size;

c) the particle size standard deviation (in logarithmic units) at the site of sampling on the Moon depends on a regolith layer overall thickness (Stacheev, 1979).

Summarized data of granulometric composition parameters of the lunar soil are listed in Table.1. The soil granulometric composition degree of inhomogeneity considerably influences the soil physical and mechanical properties. The degree of inhomogeneity can be represented as an average particle size to effective particle size ratio. An effective particle size is the size of such particles the total area of which in the soil mass unit is equal to the total area of all the soil particles.

Table 1 - Parameters of the lunar soil granulometric composition

Soil sample	Average particle size		Particle size standard deviation	Effective particle size,	Degree of inhomogeneity
	da, mm	lg da	(in logarithmic units)	de, mm	K=da/de
Luna-16	0,085	-1,071	0,623	0,0303	2,81
Luna-20	0,077	-1,113	0,816	0,0132	5,83
Apollo-11	0,098	-1,008	0,620	0,0354	2,77
Apollo-12	0,118	-0,928	0,586	0,0474	2,49
Apollo-14	0,138	-0,860	0,677	0,0409	3,38
Apollo-15	0,061	-1,215	0,536	0,0284	2,15
Apollo-16	0,153	-0,815	0,885	0,0192	7,97
Apollo-17	0,079	-1,102	0,747	0,0179	4,41

More detailed investigation of the particles distribution by their size for the lunar soil at the sites of the stations "Luna-16" and "Luna-20" landing revealed increasing average particle size with the depth of soil sampling. But the effective particle size changes a little, with a. variation of 0,06- 0,09, which is 3-6 times smaller than the variation of the average particle size. That is why the effective particle size can serve as one of the main factors defining soil granulometric composition. Granulometric composition inhomogeneity factor values depend on regolith layer thickness at the regions of soil sampling. The same correlations are revealed at the sites of the soil sampling within the "Apollo" program. Thus despite a wide range of granulometric composition of soil samples from different lunar regions, there are common regularities; the most important for the evaluation of physical and mechanical properties are the relatively constant particle size at the sampling site and granulometric composition inhomogeneity factor dependence on the regolith layer thickness.

3. Bulk density and void ratio

The main factor that determines the physical characteristics of a lunar soil sample is the degree of packing, as estimated by the void ratio (i.e., ratio of void volume to solid volume). In Table 2, the bulk density, void ratio and relative deformation for soil samples delivered by Apollo 11, 12, 14, 15 and Luna 16,20 spacecrafts are listed.

Table 2 - Bulk density and void ratio

Lunar soil sample	Bulk density, g/cm^3		Void ratio		Density of grains for void ratio g/cm^3
Condition of soil	Loose	Compact	Loose	Compact	
Apollo 11	1.36	1.8	1.21	0.67	3.01
Apollo 12	1.15	1.93			
Apollo 14	0.89 0.87	1.55 1.51	2.26 2.37	0.87 0.94	2.9 2.93
Apollo 15	1.1	1.89	1.94	0.71	3.24
Luna 16	1.115	1.793	1.69	0.67	3
Luna 20	1.040	1.798	1.88	0.67	3

In the papers (Carrier, 1991) the following best estimates for the average bulk density of the lunar soil in the intercrater areas of the lunar surface have been recommended (Table 3).

Table 3 - Average bulk density of the lunar soil in the intercrater areas

Average bulk density, g/cm^3	Depth range, cm
1.5	0 - 15
1.58	0 - 30
1.66	0 - 60
1.74	30 - 60
1.9	300

4. Compressibility and shear strength

Compressibility and shear strength parameters of the lunar soil samples were measured under different packing conditions, thus permitting the determination of general trends and relations of the physical and mechanical properties. Average values of the physical and mechanical properties of the lunar soil samples when compressed under static pressure are given in Table 4.

Table 4 - Average compressibility and shear strength parameters of delivered lunar soil samples

Soil Parameters	Void Ratio			
	>1.3	1.3 - 1.0	1.0- 0.9	<0.9
Coefficient of compressibility, (1/MPa)				
Cohesion, (kPa)	>40	20	8	<3
Angle of internal friction, (deg)	<1	1-1.5	1.5-2.5	>2.5
	<10	10-15	15-20	>20

The basic characteristics of the compressibility and shear strength parameters of the lunar soil samples are the following:

1. The physical and mechanical properties of lunar soil samples returned from different regions of the Moon are rather similar;
2. The maximum compression of the soil occurs during the initial loading. Elastic rebound of the soil proved not be high, being on the average lower than one percent of the initial strain value. Under repeated loading, the additional compression is of no consequence either;
3. The main factors that control the lunar soil packing process is particle sliding and tighter compression of soil particles and aggregates. When compressed by a pressure ranging from 50 to 100 kPa, the process of bringing

together the particles as well as increasing the number of their contacts is nearly complete, and further soil packing proceeds due to distortion of the particles at the points of contact;

4. The shear strength of the soil is described clearly enough by the Mohr-Coulomb formula. However, the parameters of shear strength depend considerably upon the degree of soil packing. In a loose state the soil has a small cohesion and angle of internal friction. As it is packed more tightly, the angle of internal friction and cohesion increase, and non-linearity is apparent in the shear strength envelope;
5. Soil deformation due to a localized load, applied to loose soil, corresponds most fully to local shear failure or punching failure. For dense soil, the deformation to a large extent corresponds to general shear failure;
6. The study of physical and mechanical properties of lunar soil makes it possible to determine the range of objective regularities that are, combining granulometric composition parameters and physical and mechanical factors. Relative setting, angle of internal friction, are in good agreement with the logarithm of effective particle size. Cohesion of soil models is in good agreement with the degree of inhomogeneity.

The in situ properties of lunar soil were obtained, using spacecraft (Luna-9,13, Surveyor, Lunokhod-1,2 rovers) and by "Apollo" astronauts. The Lunokhod operations resulted in making 1000 measurements of physical and mechanical properties of the soil surface. The measurements were made in different locations on the lunar surface, including craters, stone scatterings, isolated stones laying on the horizontal parts of the surface, as well as on the slopes.

The in situ lunar soil structure was estimated by visual evaluation of the nature of its distortion caused by the Lunokhod's chassis.The approximate evaluation of granulometric composition of the soil was done according to the wheel tracks in the surface. Noticeable imprints in the soil can only occur if the average particle size is significantly smaller then the parts of the wheel that are is contact with the soil.

When all of those factors were considered, it was concluded that the in situ soil is similar to a category of dusty sands and is subject to considerable packing under the impact of natural factors of the near-Moon space and the processes of the lunar surface formation. In addition, the variations in the global geomorphological settings between the mare and highland regions on the Moon have little influence, if any, on the processes of deposition and formation of the uppermost layer of soil. Therefore, typical soil properties can be defined.

The in situ physical and mechanical properties of lunar soil are summarized in Table 5.

Table 5 - The in situ physical and mechanical properties of lunar soil

Soil parameters	Void ratio				
	>1.3	1.3-1.0	1.0-0.9	0.9-0.8	<0.8
Bearing capacity, kPa	<7	7-25	25-36	36-55	>55
Cohesion, kPa	<1.3	1.3-2.2	2.2-2.7	2.7-3.4	>3.4
Angle of internal friction, deg.	<10	10-18	18-22	22-27	>27
Relative frequency of occurrence (%)	0.005	0.25	0.3	0.3	0.15
Typical locations on the Lunar surface	Isolated bumps and small beds of fine-grained material	On edge of fresh craters with small dimensions; on steep slopes	On elements of very eroded craters	Inter-crater areas	In areas of shallow depth of re-worked soil; stone-like formations, isolated stones

The main factors that controls the mechanical properties of soil in situ is its degree of packing, characterized by its void ratio. The void ratio for soil in situ was determined on the basis of experimental measurements of bearing capacity versus. void ratio made on terrestrial simulants chosen according to the results of studying the physical and mechanical properties of lunar soil samples delivered to Earth.

On the lunar surface a void ratio of 0.8-1.0 is most frequently encountered. This in situ conditions are characteristics of location with a relatively even surface and uniform relief. Looser soil may be observed in locations that exhibit crater-forming processes and other forms of relief, which produce considerable slopes. Extremely loose lunar soil is hardly found in situ. The location of very dense soil with void ratios less then 0.8 are distributed over the lunar surface, which is evidence of diverse processes which took place in the formation and the packing of the uppermost lunar layer.

In most cases (80%), the lunar soil is homogeneous to depth of 10 cm. Inhomogeneity of the soil structure is accounted for by hard outcrops, conglomerations of stones on the surface, particularly near certain craters and probably by marked stratification as well.

Lunar soil with a bearing capacity of 25-55 kPa is the most widespread (60%). These locations are characteristics of a relatively even surface and intercrater areas. Bearing capacity of less then 25 kPa can be observed on the rims of crater formations and on slopes steeper than 10 degrees (Bazilevsky *et al*., 1984).

Recommended typical values of lunar soil cohesion and friction angle are given in Table 6 (Carrier et al., 1991).

Table 6 - Typical values of lunar soil cohesion and friction angle

Depth range, cm	Cohesion, kPa		Friction Angle		Void Ratio
	Average	Range	Average	Range	
0-15	0,52	0,44-0,62	42	41-43	1,07±0,07
0-30	0,90	0,74-1,1	46	44-47	0,96±0,07
30-60	3,0	2,4-3,8	54	52-55	0,78±0,07

The physical and mechanical properties of a soil on depth are defined by peculiarities of soil layers. The information received from seismic experiments shows presence of several typical layers. The top layer has thickness of 2-12 m. With a speed of distribution of longitudinal waves of 100 m/s. The last layer has a thickness of 18-38 m and the speed of longitudinal waves in this layer is 300 m/s.

On the whole, the results of the lunar study of soil physical and mechanical properties based on the samples delivered to the Earth and measurements made in situ are in very good agreement and demonstrate that the processes of lunar soil formation have very much in common over vast areas. The data acquired may serve as a basis for developing soil simulants intended for setting up modern space technology for further investigation and exploration of the Moon.

References

Bazilevsky A.T., Grebennik N.N., Gromov V.V. *et al*. (1984) Dependence of Physical and Mechanical Properties of the Lunar Soil upon Specific Relief and Processes in Operation Sites of Lunokhod-2'. Kosm. Issled.. Vol.XXII, N2.

Carrier W.D.III, (1973). Lunar soil grain size distribution. The Moon, Vol.6.

Carrier W.D.III, Mitchel J.K., Mahmood A. (1973) The Nature of lunar soil. Journal of the soil mechanics and foundations division, ASCE, vol.99, pp 813-832.

Carrier W.D.III, Olhoef G.R., Mendel W. (1991) Phisical Properties of Lunar Surface. Lunar Sourcebook. Cambridge University Press.

Cherkasov I.I., Gromov V.V. *et al*. (1967) Soil Resistometerpenetrometer of the Automatic Lunar Station Luna-13. Doklady AN USSR. Vol. 179, N4.

Cherkasov I.I. and Shvaryov V.V. (1975) The Lunar Soil, Nauka, Moscow.

Florensky C.P., Bazilevsky A.T., Zezin R.B., Polosukhin V.P. , Popova Z.V. (1978) Geologcal and morphological investigations of lunar surface. In 'Lunokhod 1'- Mobile Lunar Laboratory, Nauka, Moscow.

Gromov V.V., Leonovich A.K. Lozhkin V.A. *et al*. (1971). Mechanical properties of the lunar soil sample brought by the autonatic station 'Luna-16', Kosm. Issled, Moscow, Vol. 9, N 5.

Gromov V.V., Leonovich A.K., Shvarev V.V. *et al*. (1979). The results of investigation of the phisical and mechanical properties of the lunar soil in the nitrogen medium. In: Regolith from the highland region of the Moon; Nauka, Moscow, pp. 686-690.

Gromov V.V., Zabavnikov N.A., Kemurjian A.L., *et al*. (1986) Moving along the Lunar and Planets' Soil. Mashinostroyeniye, Moscow.

Gromov V.V. (1999) Physical and mechanical properties of lunar and planetary soils. Laboratory Astrophysics and Space Research, P.Ehrenfreund et al.(eds.), Kluwer Academic Publishers. Printed in the Netherlands.

Gromov V.V., Carrier W.D. (1992) Mechnical properties of the lunar soil and simulants. Proceeding of Space 92. Denver.

Kemurjian A.L., Gromov V.V., Cherkasov I.I. *et al*. (1976) Automatic Stations for Examination of the Surface Mantle of the Moon. Mashinostroyeniye, Moscow.

Kemurjian A.L., Gromov V.V., Kazhukalo I.F. *et al*. (1993) Planet Rovers. Mashinostroyeniye, Moscow.

Krotikov V.D., Troitsky V.S. (1963) Radio-Emission and the Moon's Nature. Uspekhy fizicheskikh nauk. Vol. 81, N4.

Krupenio N.N. (1978) Padiophysical investigation of planets, Nauka, Moscow.

Leonovich A.K., Gromov V.V., Dmitriyev A.D. *et al*. (1975) The Main Processes of Decay and Deformation of Luna Soil, in: Space Chemistry of the Moon and Planets. Nauka, Moscow.

Stacheev Y.I. (1979). Regularities in lunar particle size distributions. In: Regolith from the highland region of the Moon, Nauka, Moscow.