INVESTIGATION OF SIMULATION AND MECHANICAL CHARACTERIZATION OF WATER-BEARING LUNAR POLAR REGOLITH

by

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Original scientific paper
https://doi.org/10.2298/TSCI2502325Z

It is of great significance for human to find the direct evidence of water existing on the Moon and understand the Moon better. China plans to launch the Chang'e-7 probe to carry out unmanned sampling and in-situ analysis in the Lunar south pole. In order to ensure the success of the mission, it is necessary to carry out sampling simulation experiments adequately on the ground. However, the simulation of water-bearing lunar regolith is the basis for the experiment. In this paper, the simulation and preparation process of water-bearing lunar regolith are studied in terms of the physical and mechanical properties. The uniformity of water distribution and low temperature water migration characteristics of water-bearing lunar regolith is analyzed. On the basis, the mechanical properties of the water-bearing lunar regolith are tested. The mechanical properties such as compressive strength, tensile strength and shear strength of the water-bearing lunar regolith are obtained, which provides the polar sampling tests.

Key words: *lunar pole, water-bearing regolith, simulation and preparation, mechanical properties*

Introduction

As the unique satellite of the Earth and the closest extraterrestrial object to the Earth, the Moon has always been the primary target of deep space exploration all over the world. In 1961, Watson first put forward the hypothesis of the existence of water on the Moon. He believed that the surface temperature of the lunar permanent shadow regions is about 40 K (–233 °C) [1, 2]. It is possible that water ice exists in the form of a mixture of ice and regolith. In 1994, the results of neutron spectroscopy by both the lunar explorer and the lunar reconnaissance orbiter (LRO) showed that the abundance of hydrogen was extremely high in the high latitudes of the Moon [3-6]. The data from neutron spectroscopy and reflectance spectroscopy showed that the lower the temperature, the higher the water ice content. The water ice content on the lunar surface is between 0.2%~10% [7-9]. Subsequently, the Lunar Crater Observation and Sensing Satellite (LCROSS) hit the lunar surface and sputtered out the 2~3 m lunar regolith

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material on the lunar shallow surface. Near-infrared spectroscopy showed that the water content was 5.6 ±2.9 wt.% [10], providing direct evidence of the existence of water.

The on-ground simulation of water-bearing lunar regolith and its mechanical properties are the prerequisites and guaranteeing foundation for the exploration of water-ice subsistence in lunar soil. In terms of water-bearing lunar regolith simulation, Gertsch *et al.* [11] used JSC-1 simulant to find that the higher the water content and the lower the temperature, the greater the uniaxial compressive strength. Atkinson *et al.* [12] found that the uniaxial compressive strength value of the simulated water-bearing lunar soil at 77 K was 37.15 MPa. That was quite different from the test results obtained by Kleinhenz *et al.* [13]. The Colorado University of Ores and Ore mines found that with the increase of moisture content, both the uniaxial compressive strength and the Brazilian tensile strength increased. Jiang *et al.* [14] analyzed the impact of water content rate and particle gradation of TJ-1 simulated lunar soil on the mechanical properties by experiments. Then the relationship between strength parameters and water content rate was established. He *et al.* [15] found that the effective elastic modulus of the frozen simulated lunar soil increased with the increase of water content rate in the linear elastic stage. While the frozen simulated lunar soil with a higher water content rate exhibited brittle failure characteristics in the failure stage.

At present, certain physical and mechanical tests have been carried out on simulated water-bearing lunar soil. However, most of the research is on lunar mare soil under low density conditions. The research on the simulation of lunar polar regolith and the physical properties of water-ice substances is less. It is necessary to analyze the simulation, physical and mechanical properties of water-bearing lunar soil in the polar region. In this paper, based on the highland lunar soil as the raw material, the basic characteristics of the raw material are studied. Then the simulation of water-bearing lunar soil and the preparation of test specimens are carried out. The low temperature water-bearing simulated lunar soil is obtained through gradient refrigeration. Subsequently, mechanical property tests are carried out to obtain the characteristic parameters of the water-bearing simulated lunar polar regolith with envelope characteristics, supporting for the tests of ground sampling and analysis of the mission.

Methods of simulation and preparation

Basic characteristics of raw materials

Mineral and chemical compositions. Based on the mineral and chemical compositions of the highland lunar regolith, the selected raw materials of the lunar polar regolith simulant are mainly composed of anorthosite and supplemented by basalt. The main mineral and chemical compositions are shown in tab. 1.

Physical and mechanical properties. The physical and mechanical parameters of raw materials mainly include particle morphology, as shown in fig. 1, particle size distribution, specific gravity, density, cohesion and internal friction angle. The cohesion force shows an increasing trend with the increase of relative density. The values of the parameters are shown in tab. 2.

Preparation of water-bearing lunar regolith samples

Based on the aforementioned raw materials, to adapt to the different conditions of tests, fig. 2, samples of lunar polar regolith simulant with water content of 3%, 4%, and 8.5% were prepared in this paper. The sample preparation process of the water-bearing lunar polar regolith simulant is as follows:

Table 1. Mineral and chemical compositions of raw materials

Ingredients	Basalt [%]	Anorthosite [%]	Lunar highland regolith [%]
SiO_2	47.79	65.13	45.1
Al2O3	16.32	19.31	26.8
CaO	6.96	6.42	15.6
FeO	0	0	5.4
Fe_2O_3	12.38	1.29	0
MgO	6.89	0.06	5.7
TiO_2	1.07	0.04	0.60
MnO	0.33	0.01	0.22
Na_2O	5.39	4.97	0.43
Cr_2O_3	0	0	0
K_2O	2.47	2.76	0.14
P_2O_5	0.40	0.01	0.10

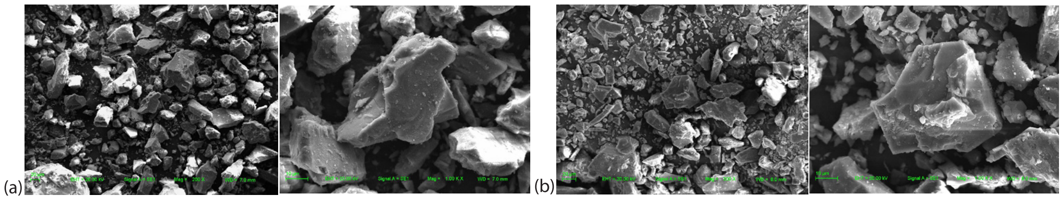

Figure 1. Surface morphology of raw materials; (a) basalt and (b) anorthosite

Table 2. Physical and mechanical properties

Parameters	Value
Particle morphology	Angular, subangular
Range of particle size [mm]	0~1
Specific gravity [gcm^{-3}]	2.73 for basalt, 2.74 for anorthosite
Minimum dry density [gcm^{-3}]	1.373
Maximum dry density [gcm^{-3}]	1.898
Cohesion (kPa, relative compactness: 74%~99%)	11.47~49.95
Internal friction angle (°, relative compactness: 74%~99%)	40.99~47.64

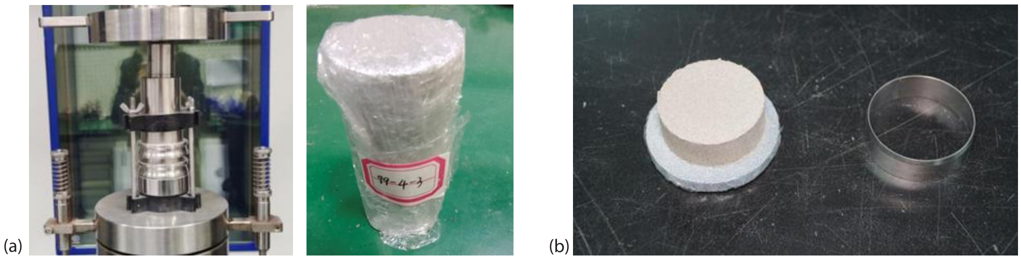

Figure 2. Specimens for tests; (a) specimens for uniaxial compressive tests and (b) specimens for tensile and shear tests

Detection of raw material properties. The particle size, particle morphology and initial water content of the raw materials are mainly tested to ensure that the raw materials meet the requirements.

Weighing and mixing of the raw material. According to the required gradation ratio, the simulated raw material of different particle sizes is weighed, mixed and stirred. To ensure the fully mixing, the raw materials are stirred more than 20 minutes per 30 kg.

Water mixing and stirring. According to the preliminary calculation of water content, the mass for adding water is given:

$$M_{\mathrm{w}} = M_{\mathrm{d}} \frac{W}{1-W} \tag{1}$$

where M_{w} is the mass of water added, M_{d} – the mass of dry simulant, and W – the water content. Considering the lose of the stirring, the mass of water actually added is 1.05 times M_{w}.

Stir the weighed dry simulant. During the stirring process, the weighed water is atomized to mix the dry simulant. After the water is mixed completely, the mixed simulant will be stirred for more than 30 minutes.

Detection of water content. At least three samples (5~10 g per sample) are randomly selected to detect the water content. When the water content is controlled within the allowable range of error, it is qualified; Otherwise, continue to add the atomized water, and detect as aforementioned until the water content meeting the requirements.

Filling and compaction. Different sample molds are loaded into water-bearing soil that meets the requirements. The water-bearing simulant is filled and compacted layer by layer. Dismantle the molds and take out the molded specimen. Wrap the samples with plastic wrap and mark it. Then place the samples in a freezer at –30 °C for freezing.

Use the aforementioned steps to prepare the other samples.

Installation of temperature sensors. Select the last prepared sample as the accompanying sample, make a hole in the center of the sample, and install a temperature sensor in the accompanying sample. The temperature measurement range of the sensor is –200~100 °C.

Gradient refrigeration. In the freezing process of the water-bearing lunar polar regolith simulant, water migration occurs. That is, water will migrate to the location where the temperature is lower. The larger the initial freezing temperature difference, the more obvious the phenomenon of water migration in the freezing process, as shown in fig. 3, T_i is the initial temperature. Considering the uniform of water distribution and the preparation efficiency of the samples, they are frozen by three-stage gradient refrigeration (–30 °C, –80 °C, and –196 °C), as shown in fig. 4.

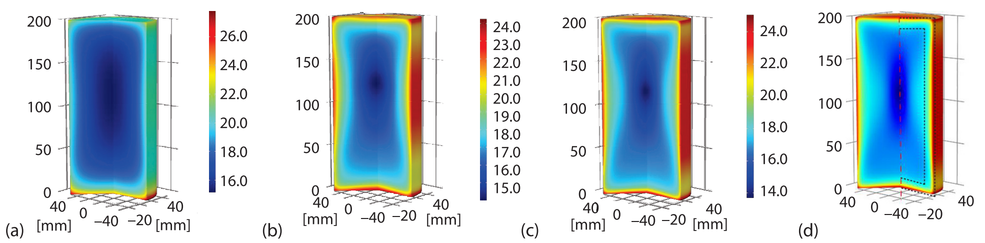

Figure 3. Water distribution of samples under different initial temperature; (a) T_i = –10 °C (b) T_i = –30 °C (c) T_i = –50 °C, and (d) T_i = –80 °C

Figure 4. Gradient refrigeration of the specimens; (a) primary refrigeration, (b) secondary refrigeration, and (c) tertiary refrigeration

Result and discussion

Uniaxial compression, Brazilian splitting and shear tests are carried out using the previous prepared samples. The failure modes of the specimens after the tests are shown in fig. 5, and the results are shown in tab. 3.

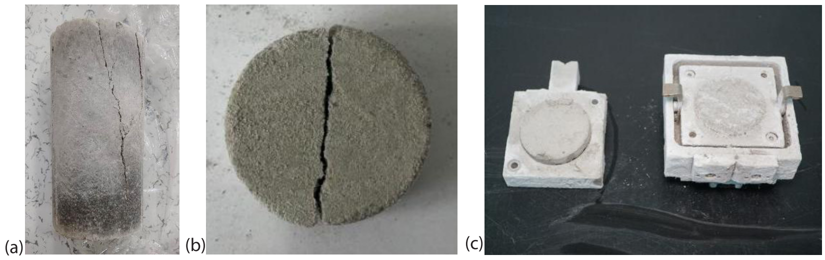

Figure 5. Failure modes of the specimens; (a) compression failure, (b) Brazilian splitting failure, and (c) shear failure

Table 3. Reference values of mechanical properties

Serial	Preparation parameters			Uniaxial compresive strength [MPa]		Tensile strength [MPa]		Shear characteristics	
	Water content	Compactness	Temperature	Range value	Average value	Range value	Average value	Cohesiveness [kPa]	Internal friction angle
1	3 wt.%	65%	–180 °C	2.1-2.7	2.44	0.32-0.48	0.41	276.23	50.99°
2	3 wt.%	74%	–180 °C	2.5-3	2.81	0.45-0.62	0.54	285.72	52.03°
3	3 wt.%	99%	–180 °C	4.7-5.6	5.15	0.67-0.94	0.83	299.28	53.79°
4	4 wt.%	99%	–180 °C	13.4-20	17.23	0.88-1.46	1.13	322.77	56.12°
5	8.5 wt.%	99%	–180 °C	29.0-37.0	32.02	2.02-3.15	2.72	1842.20	68.83°
6	10 wt.%	99%	–180 °C	42.4-45.4	43.83	3.78-4.41	4.06	1917.62	69.90°

The results show that with the increase of compactness, the uniaxial compressive strength, tensile strength, cohesion and internal friction angle of the specimen increase. The greater the compactness, the more obvious the increase in strength value. With the increase of water content, the uniaxial compressive strength, tensile strength, cohesion and internal friction angle of the sample increase as the same. In addition, the water-bearing lunar polar regolith simulant with low water content and compactness showed obvious plastic characteristics. With the increase of water content and compactness, the brittle failure characteristics of the water-bearing lunar polar regolith simulant are significantly enhanced, which is consistent with the conclusions obtained in [15].

Conclusion

Based on the compositions of the lunar highland regolith, it was determined that the raw materials of water-bearing lunar polar regolith simulant are mainly anorthosite and supplemented by basalt. Then the basic physicochemical and mechanical properties of the raw materials, such as composition, particle morphology, particle size distribution, specific gravity, density, cohesion and internal friction angle are analyzed. On the basis of the raw material, the simulation and preparation processes of water-bearing lunar polar regolith are determined. Samples with different parameters and low temperature are prepared. Finally, the mechanical properties of the water-bearing lunar polar regolith simulant with different compactness and different water content are analyzed by carrying out the mechanical property tests. The characteristic parameters of the water-bearing lunar polar regolith simulant with enveloping properties are obtained, which supports the ground sampling and analysis experiments of the Chang'e-7 mission.

Acknowledgment

The work was supported by the National Natural Science Foundation of China (Nos. U2013603, 52434004, U21B2072), and the Scientific Instrument Developing Project of Shenzhen University.

Nomenclature

M_d – mass of dry simulant, [g]
M_w – mass of water, [g]
W – water content

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Paper submitted: November 24, 2024
Paper revised: November 30, 2024
Paper accepted: December 11, 2024