PREPARATION AND EXPERIMENTAL STUDY OF AQUEOUS SIMULATED LUNAR SOIL IN LUNAR POLAR REGION

by

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The polar region of the Moon has great scientific value and research significance because of abundant mineral resources, possible water and ice and unique geographical location resources, and is becoming a new hot spot in the new round of international lunar exploration. China's Chang 'e-7 probe will also go to the polar region of the Moon carry out the sampling and detection mission of water-bearing lunar soil. In this paper, a set of water-bearing simulated lunar soil preparation system in polar regions is proposed, and the preparation and research of water-bearing simulated lunar soil in polar regions are carried out from several aspects, such as preparation of water-bearing simulated lunar soil, research and development of vacuum system, design of simulated lunar soil bucket and vacuum test. The test results show that the water-bearing simulated lunar soil developed by the system has no abnormal situation in vacuum environment, and can be applied to the subsequent ground test of Chang 'e-7 detector

Key words: *water-bearing simulated lunar soil, preparation, validation*

Introduction

As the closest celestial body to the Earth, the Moon is the first choice for human deep space exploration [1]. In recent years, the goal of international lunar exploration is mainly concentrated in the south pole of the Moon [2], expecting to establish scientific research stations in the south pole of the Moon. The polar region of the Moon has great scientific value and research significance because of abundant mineral resources, possible water and ice and unique geographical resources, and is becoming a new hot spot in the new round of international lunar exploration [3-5]. Up to now, there have been only two Antarctic explorations in the world. In August 2023, Russia's Luna25 collided during the orbit change, which led to the failure of the exploration mission originally scheduled to land on the South Pole of the Moon. In the same month, India's *Yuechuan-3* probe successfully landed at the south pole of the Moon, but lost contact after landing.

China has successfully completed the sampling and return mission of the third phase of lunar exploration. In December 2020, the Chang 'e-5 probe successfully landed in the lunar sea area in the northwest of the Moon [6, 7], and successfully obtained 1731 g lunar soil samples [8-10]. In June, 2024, China's Chang 'e-6 probe successfully completed the first human

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return mission of sampling the back of the Moon in the South Pole-Aitken (SPA) basin of the Moon, with a sampling amount of 1935.3 g. The fourth phase of China's lunar exploration project plans to go to the polar region of the Moon explore the lunar soil water ice [11]. The Chang 'e-7 exploration mission will also realize the four-in-one comprehensive exploration of *circling*, *falling*, *patrolling* and *leaping* the south pole of the Moon [12].

Compared with the middle and low latitudes, the temperature in the permanent shadow area of the polar region of the Moon is extremely low [13], and the low temperature makes it impossible for water molecules to escape through thermal movement [14, 15], which has always been considered as the most likely area where water ice occurs, and it is speculated that water ice occurs in frozen lunar soil. Therefore, the preparation of water-bearing lunar soil ground simulation has become the key link in the subsequent Chang 'e-7 ground test verification.

At present, China Academy of Space Technology is carrying out in-situ rapid prediction of water-bearing lunar soil and its drilling performance research, Harbin Institute of Technology has carried out research on preparation device of water-bearing simulated lunar soil, and State Key Laboratory of Frozen Soil engineering, Chinese Academy of Sciences is carrying out research on physical and mechanical properties of frozen simulated lunar soil in lunar polar region. At present, only the physical and mechanical properties of water-bearing lunar soil have been studied abroad. All the aforementioned studies involve the preparation and ground verification of simulated lunar soil with low temperature and water content.

In this paper, a preparation method of simulated lunar soil containing water at low temperature is studied, and the loading equipment of simulated lunar soil suitable for vacuum environment is designed and the vacuum performance test is carried out, which provides the object and support for the subsequent test verification.

Environmental characteristics of spherical polar region

According to the topographic data obtained by the existing remote sensing mission, the topographic map of the middle and low latitudes of the Moon (between 60 north and south latitudes) is shown in fig. 1. It can be seen from the elevation map that the topography in the middle and low latitudes is mostly a large area of Moon Sea and mountains, and their distribution is relatively independent, so for most areas, the elevation change in a small range is small. China's Chang 'e-3 probe landed in the Moon Sea area at 19.51 north latitude and 44.12 west longitude.

The region above 75 north and south latitude of the Moon is defined as the polar region of the moon. Compared with the middle and low latitudes, the topography of the polar region is more complex, with larger elevation difference and greater fluctuation, as shown in fig. 2.

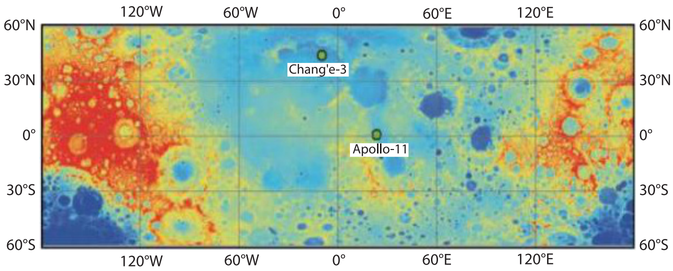

Figure 1. The elevation of lunar low latitude area

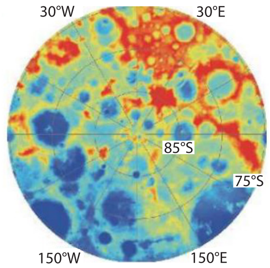

Figure 2. The elevation of lunar poles

The temperature in the polar region of the Moon directly depends on the illumination on the lunar surface. Compared with the middle and low latitudes, the illumination in the polar region is characterized by low solar height angle and great influence by topography [11, 12]. The idea of water ice on the Moon was put forward by Watson of America in 1961 [13]. Most of the water ice on the Moon occurs in the water-bearing lunar soil in the permanent shadow pit in the polar region of the Moon. Scientists at home and abroad have studied the occurrence areas of lunar water ice by radar, spectral detection, neutron detection and other means, and screened out the distribution of possible water ice areas. According to the temperature environment of the permanent shadow pit in the polar region of the Moon, the water-bearing characteristics of lunar soil in the polar region and the requirements of sampling and exploration tasks in the polar region, the temperature of the permanent shadow pit to be operated in the fourth phase of lunar exploration is –223 °C or even lower.

Design of test system

In order to simulate the characteristics of water-bearing lunar soil in the polar region of the Moon and provide objects for the ground verification test of Chang 'e-7 exploration mission, Beijing Spacecrafts. developed and designed a set of water-bearing simulated lunar soil ground test system. The system is mainly composed of vacuum refrigeration system, water-bearing simulated lunar soil and simulated lunar soil bucket. Vacuum refrigeration system consists of tank, refrigeration system, temperature detection system, vacuum pump unit, monitoring system and installation platform, as shown in the fig. 3.

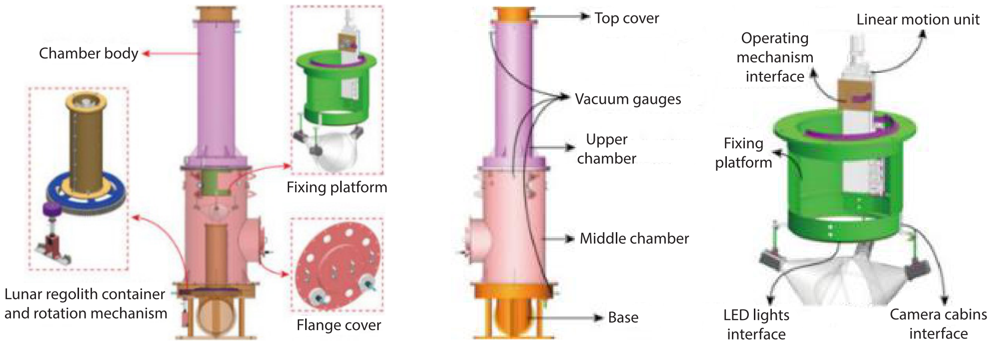

Figure 3. The elevation of lunar poles

The tank body of the vacuum tank is divided into an upper section, a lower section and a base, wherein, a simulated wall connecting plate is sandwiched between the upper section and the lower section, and sealing rings are installed between each section, and the smearing of sealing grease should be checked every time the tank is opened to ensure the air tightness of the vacuum tank. The main function of refrigeration system is to provide cold source for vacuum tank and simulated lunar soil, so as to realize the simulation of low temperature environment. The main function of the installation platform is to fix and bear the lunar soil bucket. Heat insulation pads are arranged on the installation platform, so as to improve the cooling efficiency of water-bearing lunar soil.

The preparation method of water-bearing simulated lunar soil is, fig. 4:

– Basalt and plagioclase with different particle sizes are mixed according to a certain proportion.

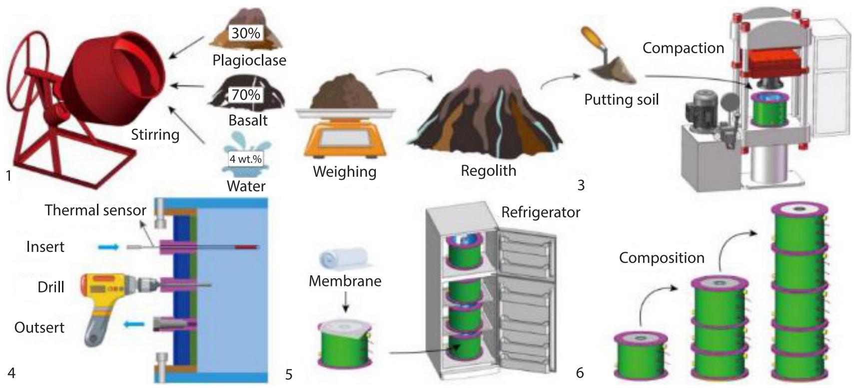

Figure 4. Preparation process of water-bearing simulated lunar soil

– Adding a certain amount of water according to the weight ratio and mixing it with dry soil until random sampling is carried out for three times, and the detection results of water content of each time are consistent.
– The simulated lunar soil with water content is packed in the lunar soil bucket, and pressed by a press, and the random detection of water content is continuously carried out during the pressing process.
– Splicing the pressed water-bearing lunar soil according to sections until the required height.
– Placing the temperature sensor inside the lunar soil bucket and ensuring that the temperature sensor can fully contact with the water-bearing lunar soil.
– The water-bearing lunar soil is cooled by gradient cooling.

The factors to be considered in the design of water-bearing lunar soil bucket include:
– the influence of disturbance during the test,
– the strength of lunar soil bucket itself in the process of lunar soil compaction, and
– exhaust of lunar soil in vacuum environment.

The preparation of water-bearing simulated lunar soil is to provide test objects for water ice drilling and sampling of Chang 'e-7 lunar soil. Therefore, it is necessary to consider the influence of temperature rise during drilling on the whole barrel of lunar soil in the design process of lunar soil barrel. Therefore, the temperature rise during drilling is simulated and analyzed. Under the current drilling speed and power, the disturbance radius of water-bearing lunar soil with water content of 5% is 50 mm, fig. 5.

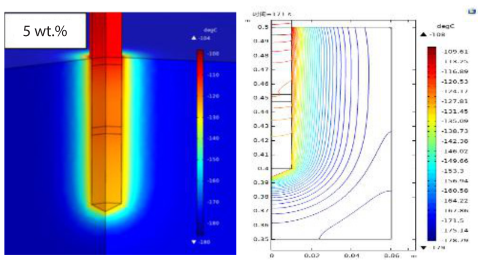

Figure 5. Disturbance range simulation analysis

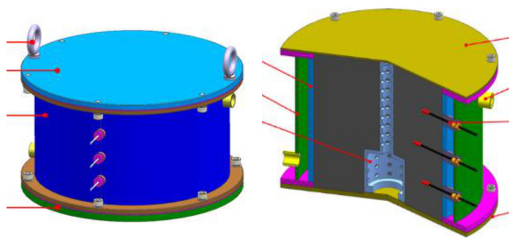

Figure 6. Structure of simulated lunar soil bucket

In order to facilitate the compaction of water-bearing lunar soil, the whole simulated lunar soil bucket is designed as a subsection structure, and the height of each section is

300 mm, fig. 6. The structure of each simulated lunar soil barrel is shown in the following figure, which mainly includes barrel, core barrel, upper and lower flange covers, lifting rings, sealing gaskets, temperature sensors and other parts. Liquid nitrogen joints are arranged at the upper and lower ends of the outer barrel, the inner barrel and the outer barrel are welded to form a liquid nitrogen cavity with hollow side walls, and a temperature sensor is introduced into the inner part of the barrel through a sensor assembly. The core barrel is fixed by screws and stops on the lower flange cover, and the outside is sleeved with a metal screen. Among them, the role of the core barrel is to provide more outgassing channels for lunar soil in vacuum environment, so as to avoid bubbling or churning.

In the process of lunar soil compaction, the inner container of lunar soil bucket will bear the vertical downward pressure brought by hydraulic press, and the transmission coefficient of the pressure is $\eta = 0.5$. The pressure on the inner container of the lunar soil bucket:

$$p = \eta P \tag{1}$$

where p is the actual pressure, P – the pressure inside the tank, and η – the transmission coefficient of the pressure. Thus, we can obtain:

$$P = 12.5 \ \text{MPa} \tag{2}$$

Through stress simulation, under the aforementioned pressure, the stress and deformation results of lunar soil bucket are shown in fig. 7. The results show that the maximum stress is 215 MPa and the maximum deformation is 0.1 mm, which is within the acceptable range.

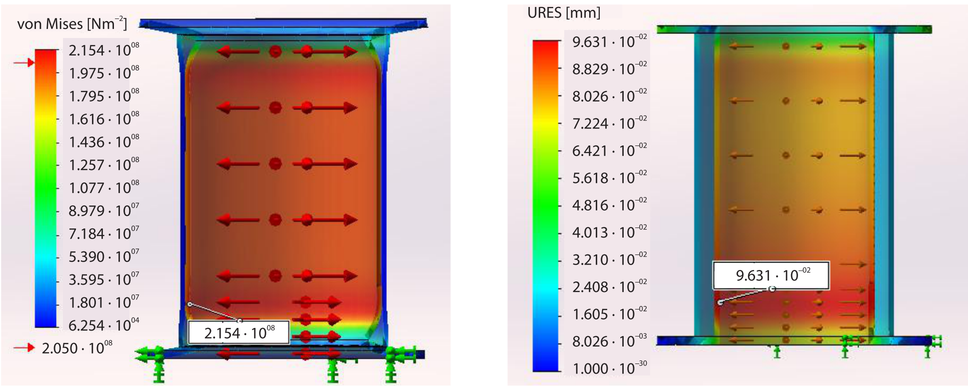

Figure 7. Stress and deformation results

Vacuum test of water-bearing lunar soil

In order to release the air slowly and fully, the strategy of reducing pressure and keeping pressure in stages was adopted in the process of vacuumizing water-bearing lunar soil, figs. 8 and 9. The details are:

- Vacuumizing from 10^5 Pa to 10^4 Pa in the first stage. Open the mechanical pump to reduce pressure, observe the vacuum state, and record the vacuum value in real time. When it reaches 10^4 Pa, the pressure is stabilized for 9 hours (the pressure is controlled between $0.9 \cdot 10^4$ Pa and $1.1 \cdot 10^4$ Pa, and the pressure is stabilized by mechanical pump).
- In the second stage, vacuum is pumped from 10^4 Pa to 10^2 Pa. Open the mechanical pump to reduce pressure, observe the vacuum state, and record the vacuum value in real time. When it reaches 100 Pa, the pressure is stabilized for 9 hours (the pressure is controlled between $0.9 \cdot 10^3$ Pa and $1.1 \cdot 10^3$ Pa and the pressure is stabilized by mechanical pump).

- In the third stage, vacuum is pumped for 8 hours to the limit. Open Roots pump and diffusion pump in turn to reduce pressure, keep pressure for 8 hours, observe the vacuum state, and record the vacuum value in real time. Observe the surface state of lunar soil and record it.
- Stop the vacuum pumps one by one, keep them closed for a certain time, observe the vacuum state, and record the vacuum value in real time for more than 8 hours.

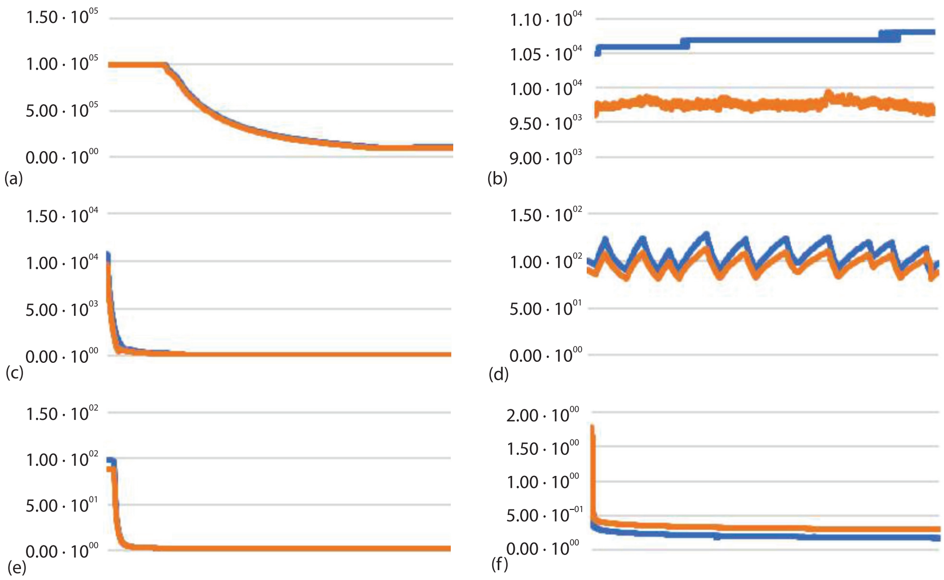

Figure 8. Vacuum during the test; (a) first stage, (b) 10000 Pa pressure maintenance, (c) second stage, (d) 100 Pa pressure maintenance, (e) process of 100 Pa to 1 Pa, and (f) the process of 1 Pa to limit

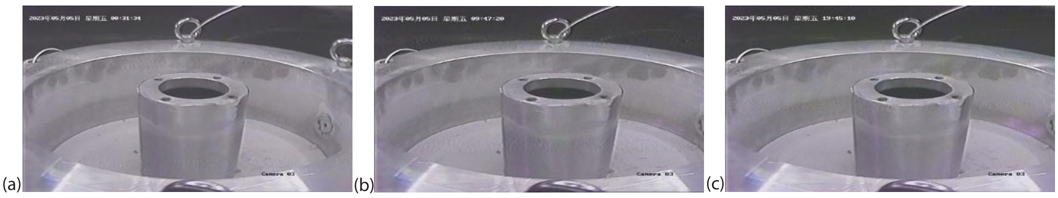

Figure 9. State of water-bearing lunar soil during the test; (a) first stage, (b) second stage, and (c) third stage

According to the aforementioned tests, we have the results:

- The surface state of water-bearing lunar soil did not change after normal pressure to 10^4 Pa and holding pressure for 9 hours;
- The surface state of water-bearing lunar soil did not change after holding pressure for 9 hours from 10^4 Pa to 10^2 Pa.
- Water-bearing lunar soil reached the limit at 10^2 Pa, and the surface state did not change after holding pressure for 8 hours.

Conclusions

Through the aforementioned experiments and studies, the following conclusions can be obtained.

– The experimental system discussed and verified in this paper can meet the needs of surface preparation of simulated lunar soil with 5% water content.
– The vacuuming regulation studied in this paper can ensure that the simulated lunar soil with 5% water content will not fluctuate, bubble, churn and jet during vacuuming, and the simulated lunar soil state will be affected.
– The vacuum pumping rules adopted in this experiment can be further extended to the ground verification of simulated lunar soil with other water content.
– After that, the test system is further improved and optimized. This includes raising the vacuum degree of the vacuum chamber to be closer to the high vacuum environment of the Moon, strengthening the research on the physical characteristics of the polar region of the lunar surface, and expanding the simulation environment to cover the coupling characteristics of multiple physical fields on the lunar surface.

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