# EQUIVALENT VERIFICATION METHOD FOR EXTREME HYPOTHERMIC ENVIRONMENT ADAPTABILITY OF LUNAR POLAR DRILL BIT CUTTING TOOLS

by

***Gui-Dong MO[a], Lu-Si WANG[a], Jun LI[a], Jun-Shan GONG[a], Yong PANG[a], Xu YANG[b], A-Bin LING[a], Xin-Xin LI[a], and Qi-Chen SUN[a]****

[a] Beijing Spacecrafts, Beijing, China
[b] Beijing Institute of Spacecraft System Engineering, Beijing, China

Original scientific paper
https://doi.org/10.2298/TSCI2502223M

*Aiming at the problems of high cost and great difficulty in verifying the performance of the drill bit cutting tools in the extreme hypothermic environment (20-40 K) of the lunar polar regions, this paper proposes an equivalent verification method based on the liquid nitrogen temperature range (–180 °C). Through a systematic analysis of the influence mechanism of extremely low temperature on the mechanical properties of lunar regolith and the performance of drill bit materials, the stable threshold of the strength of the frozen soil working condition changing with temperature is determined, and the key risk of the increase in internal stress caused by the thermo-mechanical coupling deformation of the drill bit is revealed. Based on the equivalent principle of material impact work and the compensation strategy for thermal stress increment, an equivalent verification theoretical framework with the core of kinetic energy proportional scaling and external load superposition is constructed, and a multi-dimensional test matrix covering the working conditions of dry soil and frozen soil is designed. The research results show that, by optimizing the driving parameters of the drilling tool and the load conditions, this method can effectively simulate the mechanical impact and structural stress effects of the extreme hypothermic environment on the cutting tools, providing an innovative solution for the low cost and high efficiency verification of the reliability of drilling tools.*

Key words: *cutting tool, broken blade, extreme hypothermic environment, equivalent verification*

## Introduction

The moon is making it the preferred target for human exploration of extraterrestrial bodies in the solar system, and serving as a transit base for humans to explore deep space [1]. Since the 1950's, humans have carried out approximately 118 exploration activities, with more than 20 probes conducting direct lunar exploration [2]. In recent years, the lunar polar region has become a new hotspot for international lunar exploration owing to its abundant mineral resources and the potential presence of water ice, which has significant scientific value and research significance [3-5].

Research has shown that there is a large amount of water in the giant, permanently shadowed craters at the poles of the moon [6-9], but there is still a lack of direct measurement

* Corresponding author, e-mail: sun_qi_chen@163.com

evidence to address issues such as the occurrence, content, distribution, and sources of water ice [2]. Therefore, the exploration of water ice in the lunar polar regions has become a hot topic in current international lunar exploration, including multiple missions such as volatile investigating polar exploration rover) (VIPER) in the USA, Luna 25/27 in Russia, and Chang'e-7 in China. These missions aim to collect and analyze soil samples containing water in the south pole of the moon through drilling [10].

Because there is no light, the annual average temperature can be as low as 20-40 K inside the permanent shadow craters at the poles of the moon [11], far below the lower limit of extreme low temperatures on Earth, belonging to the category of extreme hypothermic environment. The extreme hypothermic environment poses a severe challenge to exploration tasks, especially drilling tasks that come into direct contact with lunar soil. In order to ensure the reliability of the drilling tool's lunar surface work, it is necessary to conduct extreme hypothermic lunar soil drilling tests on the ground to verify the in orbit performance of the drilling tool.

Simulating aextreme hypothermic environment of 20-40 K requires the use of a liquid helium refrigerant refrigeration system, which is extremely costly. It is economically difficult to support large-scale drilling tests in extreme hypothermic environments of 20-40 K. A relatively feasible approach is to conduct equivalent validation tests in the low temperature range achievable with liquid nitrogen. According to research, there is currently no research on equivalent verification test methods for structural mechanical properties at different temperatures. This study investigates the feasibility of equivalent verification of the structural performance of drill bit cutting tools in aextreme hypothermic environment of 20-40 K within the range of liquid nitrogen refrigeration temperature, designs an equivalent verification scheme, and experimentally verifies the feasibility of the equivalent verification scheme.

## Drilling tool configuration and failure mode

The typical configuration of the lunar polar drilling tool is shown in fig. 1, which is a centrally symmetrical slender rod structure consisting of a drill bit, a sampling screw, and a drill rod. The front end of the drilling tool is the drill bit, and the tail end has a mechanical interface. The drill rod and sampling screw are designed with an outer spiral wing structure. The drill bit of the lunar polar water ice drilling tool is a cutting type drill bit, consisting of a drill bit base and cutting tools. The drill bit base and cutting tools are welded together by brazing. The sampling screw and drill rod material of the drilling tool are made of titanium alloy, the base material of the drill bit is 40Cr alloy steel, and the cutting tool material is hard alloy YG6X.

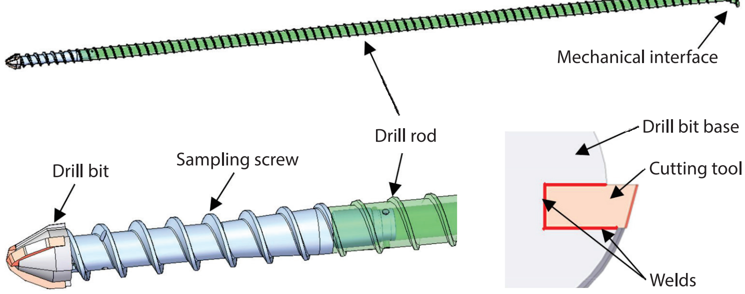


**Figure 1. Composition of drilling tool**

There are two damage forms of drill bit cutting tools: excessive wear and blade breakage. In the two failure modes, blade breakage is a random event caused by uncertain working conditions, with strong randomness. In engineering, it is necessary to avoid blade breakage of cutting tool.

## Analysis of the impact of extreme hypothermic environment

The equivalent test requires a comprehensive consideration of the impact of deep and low temperatures on the performance of both the drilled object and the drill bit.

### *Influence of extreme hypothermic environment on the mechanical properties of lunar soil*

Lunar polar drilling may encounter dry lunar soil and frozen soil.

The dry soil condition is a particulate medium, and its mechanical properties depend on the four factors of particle material, particle morphology, gradation and compactness, which are independent of temperature. Therefore, the mechanical properties of dry soil are independent of temperature.

Liu *et al.* [12] conducted a systematic study on the uniaxial compressive strength of simulated frozen soil and influencing factors in the temperature range of –10 °C to –230 °C. The research shows that under the same material composition, particle size distribution, moisture content, and compactness, as the temperature of frozen soil samples decreases, their uniaxial compressive strength gradually approaches a stable value. The strength of the samples at –180 °C and –230 °C is similar.

Therefore, in order to ensure the similarity of the strength of frozen soil conditions in the experiment, the temperature of the frozen soil material should be controlled at ≤ –180 °C.

### *Influence of extreme hypothermic environment on the mechanical properties of drill bit cutting tools*

Based on the structural of the drill bit, the influence of extreme hypothermic environment on the mechanical properties of the drill bit cutting tool mainly includes the following two aspects:

*Influence of material properties of drill bit cutting tools in extreme hypothermic environment*. For most materials, as the temperature decreases, the strength of the material will increase and the impact energy will decrease. The decrease in impact energy will increase the brittleness of the structure, especially in the case of large temperature differences where the values will vary greatly.

*Decrease of bearing performance caused by thermal coupling deformation.* The drill bit is a welded structure made of dissimilar materials. There is a significant difference in the coefficient of linear expansion between 40Cr and YG6X. As the temperature decreases, internal stress of the drill bit caused by thermal coupling deformation increases. The internal stress will be transmitted from the weld position the cutting edge, forming an initial preload and reducing the bearing capacity of the drill bit.

## Design of equivalent verification test scheme

Based on the previous analysis, the equivalent verification test design for the adaptability of extreme hypothermic environment of drill bit cutting tools was conducted at –180 °C.

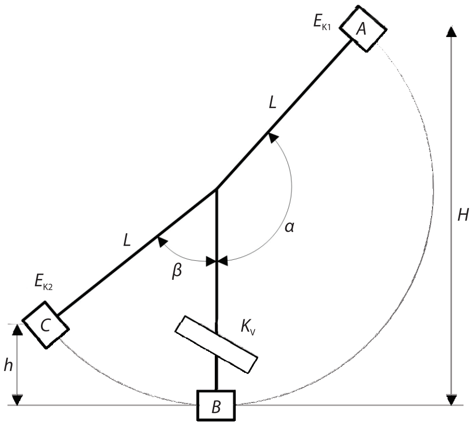


**Figure 2. Impact energy testing model**

### *Equivalent scheme for the risk of blade breakage caused by changes in material properties*

*Equivalent principle*. From the perspective of the chipping mechanism of cutting tools, their failure process is consistent with the principle of material impact energy testing, both of which are caused by structural collisions under the action of large kinetic energy, with the only difference being the structural form.

The principle of material impact energy testing is shown in fig. 2. By testing the change of the pendulum potential energy, the impact energy of the standard specimen is calculated.

According to fig. 2, there are:

$$K_V = E_{K1} - E_{K2} \tag{1}$$

where $K_V$ is the impact energy of the material, $E_{K1}$ – the initial potential energy of pendulum and $E_{K2}$ – the potential energy after pendulum impact.

The process of the drill bit cutting tool colliding with a rock block and causing the cutting edge to break. Assuming the kinetic energy of the drilling tool before the collision is $E_{ZK1}$ and after the collision is $E_{ZK2}$, the breaking energy of the drill bit cutting tool's cutting edge is:

$$K_{ZV} = E_{ZK1} - E_{ZK2} \tag{2}$$

The breaking power of the cutting edge depends on material properties and geometric configuration, given a fixed mechanical configuration, $K_{ZV}$ completely depends on material properties.

At –238 °C, the breaking energy of the cutting edge of the drill bit can be described as:

$$K_{ZV-238} = E_{ZK1} - E_{ZK2} \tag{3}$$

Under the condition where the motion state of the drilling tool, the state of the encountered rock blocks, and the collision location are all identical. The breaking energy of the cutting edge of the drill bit at –180 °C environment can be described as:

$$K_{ZV\text{-}180} = \lambda K_{ZV\text{-}238} = \lambda E_{ZK1} - \lambda E_{ZK2} \tag{4}$$

where $\lambda$ is the ratio of the impact energy of the cutting tool material at –180 °C to that at –238 °C.

From the aforementioned equations, when the pre collision kinetic energy of the drilling tool at –180 °C is $\lambda$ times that at –238 °C, the post collision kinetic energy of the drilling tool at 180 °C is also $\lambda$ times that at –238 °C. When $\lambda > 1$, $\lambda E_{ZK2} > E_{ZK2}$, which means that, the residual kinetic energy after the collision between the drilling tool and the rock block at –180 °C is higher than that at –238 °C, which is more likely to cause the cutting tool to collapse.

Therefore, when $\lambda > 1$, the method of increasing the kinetic energy of the drilling tool in the same ratio at –180 °C can cover the risk of tool breakage at –238 °C, and this method is conservative.

The impact toughness of YG6X was measured at –180 °C and –238 °C, with values of 3.927 J/cm² and 2.994 J/cm², respectively. The calculated value is $\lambda = 1.31 > 1$. Therefore, it is feasible to use the method of increasing the kinetic energy of drilling tools proportionally to equivalently verify the risk of tool breakage of the drill bit cutting tool (YG6X) in an environment of –180 °C and –238 °C.

*Equivalent method of drilling tool kinetic energy*. Drilling tools have three driving forces: rotation, feed, and impact. Therefore, the kinetic energy of drilling tool motion can be expressed as:

$$E_p = \frac{1}{2}J\omega^2 + \frac{1}{2}mv^2 + Q \tag{5}$$

where $J$ is the moment of inertia of the drilling tool, $\omega$ – the rotational speed, $m$ – the mass of the feed motion, $v$ – the feed motion speed, and $Q$ – the impact energy.

Assuming that the working speed of the drilling tool is $\omega_0$, the feed rate is $v_0$, and the impact energy is $Q_0$ at –238 °C, the kinetic energy of the drilling tool at –238 °C is:

$$E_{p-238} = \frac{1}{2}J\omega_0^2 + \frac{1}{2}mv_0^2 + Q_0 \tag{6}$$

According to the method of increasing the kinetic energy of drilling tools year-on-year, the kinetic energy of drilling tools at –180 °C is $\lambda$ times that of drilling tools at –238 °C, which is:

$$E_{p-180} = \lambda E_{p-238} = \frac{1}{2}\lambda J\omega_0^2 + \frac{1}{2}\lambda mv_0^2 + \lambda Q_0 = \frac{1}{2}J\left(\sqrt{\lambda}\omega_0\right)^2 + \frac{1}{2}\lambda m\left(\sqrt{\lambda}v\right)^2 + \lambda Q_0 \tag{7}$$

From aforementioned equations, the method to increase kinetic energy of drilling tools proportionally is to increase the rotation speed and feed rate by times, and increase the impact energy by $\lambda$ times.

### *Equivalent scheme for thermal coupling stress increase of drill bit*

The idea of equivalent verification is to calculate the internal stress increment at the cutting edge of the drill bit caused by the temperature variationsof –180 °C to –238 °C, and simulate the effect of this internal stress increment by increasing the external load during drilling:

*Calculation of internal stress at the cutting edge of drill bit caused by temperature.* Analyze the cooling process of drill bits in the temperature range below 250 °C (the annealing temperature). Comparing the results of figs. 3(a) and 3(b), the maximum thermal stress at the cutting tool tip at –238 °C is 31.3 MPa higher than that at –180 °C.

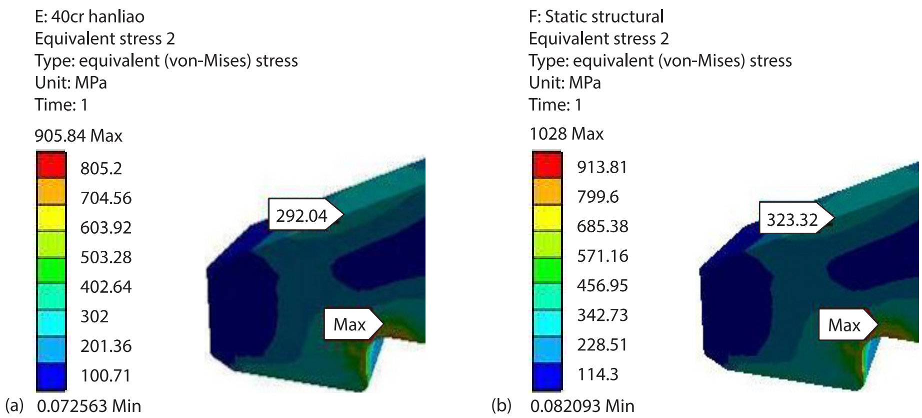


**Figure 3. Thermal mechanical coupling analysis of cutting tool; (a) 250 °C to –180 °C, (b) 250 °C to –238 °C**

*Equivalent increment calculation of drilling tool driving load.* The working stress analysis of cutting tools was carried out separately under the rated working force load (rotation of 15 Nm, impact of 2 J, feed of 150 N) and the torque condition of increasing by 1 Nm (rotation of 16 Nm, impact of 2 J, feed of 150 N). The results are shown in fig. 4.

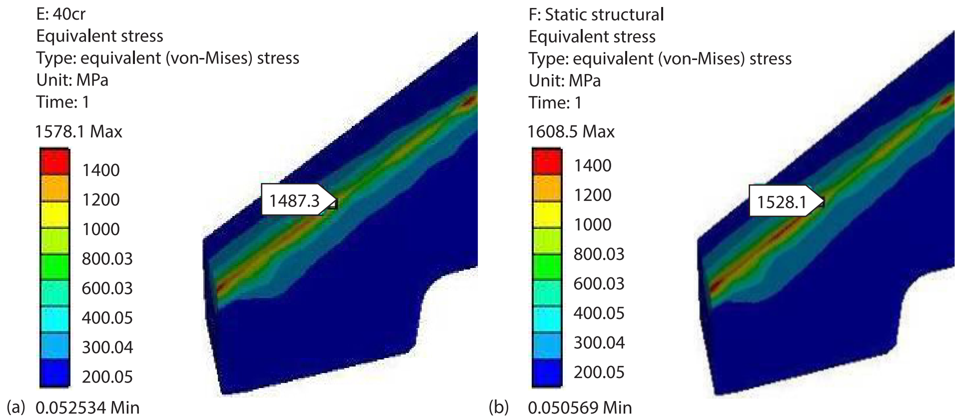


**Figure 4. Simulation results of static equivalent stress of drill bit under driving force; (a) 15 Nm, 2 J, 150 N and (b) 16 Nm, 2 J, 150 N**

Comparing the two working conditions, it is evident that with an increase of 1 Nm in rotational torque, the maximum working stress at the middle position of the cutting tool edge increased by 40.8 MPa, which is greater than 31.3 MPa. Therefore, adjusting the rotary drive torque from the limit of 15-16 Nm, and causing drilling tool blockage during the test process, can cover the risk of cutting edge collapse caused by thermal coupling stress at the cutting tool tip due to cooling from –180 °C to –238 °C.

### *Experimental matrix design*

From the equivalent theory mentioned earlier, it is evident that the equivalent verification test scheme is more rigorous compared to the real environment test at –238 °C, with a higher risk of blade breakage. Therefore, when the drill bit cutting tool does not collapse in the equivalent test, it can be concluded that the cutting tool will not collapse at –238 °C. Otherwise, it won't work.

Based on the equivalent scheme mentioned, the design of the equivalent verification test matrix for the adaptability of cutting tool inextreme hypothermic environment is shown in tab. 1.

## Experimental verification

To verify the effectiveness of the equivalent verification test plan, a comparison test was designed and conducted: an equivalent verification test at –180 °C and a real-temperature test at –238 °C. The drilling systems for the two tests are shown in figs. 5(a) and 5(b) below, respectively. The drill bit used for testing is installed at the front end of the drilling tool.

After completing the two experiments, the conditions of the drill bits are shown in figs. 5(c) and 5(d), respectively. It is evident that the cutting tips of the two drill test pieces remain intact. The outcomes of both experiments are consistent and positive, validating the logic of the equivalent verification test scheme. This means that when the drill bit cutting tool successfully completes the equivalent verification test, it can also be passed the real-temperature test.

**Table 1. Equivalent test matrix for adaptability of cutting tools to extreme hypothermic environment**

| Experimental conditions | Drilling parameters at –238 °C | | | | | | Equivalent drilling parameters at –180 °C | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Rotation speed [rpm] | Rotation torque limit [Nm] | Feed rate [mm per minute] | Feed force limit [N] | Impulse frequency [Hz] | Impact energy [J] | Rotation speed [rpm] | Rotation torque limit [Nm] | Feed rate [mm per minute] | Feed force limit [N] | Impulse frequency [Hz] | Impact energy [J] |
| Typical dry soil | 120 | 15 | 100 | 150 | 0 | – | $120\sqrt{\lambda}$ | 16 | $100\sqrt{\lambda}$ | 150 | 0 | – |
| Challenge dry soil | 120 | 15 | 100 | 150 | 0 | – | $120\sqrt{\lambda}$ | 16 | $100\sqrt{\lambda}$ | 150 | 0 | – |
| Extreme dry soil | 120 | 15 | 100 | 150 | 0 | – | $120\sqrt{\lambda}$ | 16 | $100\sqrt{\lambda}$ | 150 | 0 | – |
| Typical frozen soil | 60 | 15 | – | 150 | 10 | 2 | $60\sqrt{\lambda}$ | 16 | – | $150\lambda$ | 10 | $2\lambda$ |
| Challenge frozen soil | 60 | 15 | – | 150 | 10 | 2 | $60\sqrt{\lambda}$ | 16 | – | $150\lambda$ | 10 | $2\lambda$ |

Note: The dry soil test requires a total of more than 3 instances of blockage.

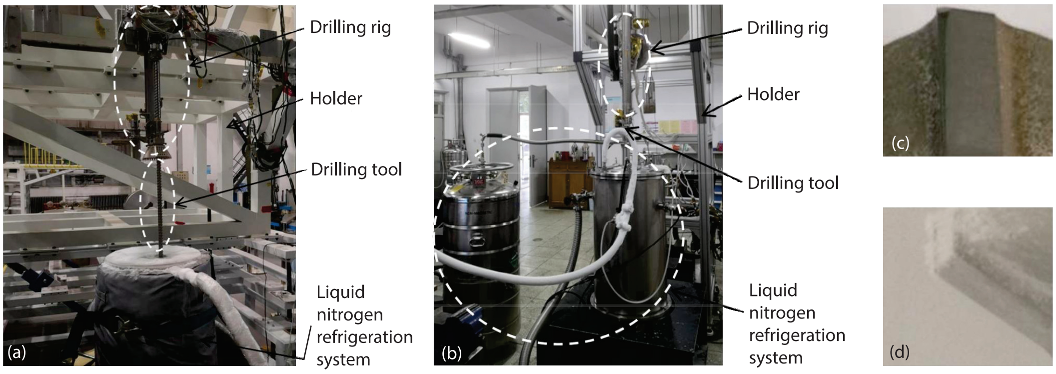


**Figure 5. Test system and results; (a) equivalent verification test system, (b) real temperature drilling test system, (c) –180 °C test piece, and (d) – 238 °C test piece**

## Conclusion

This paper addresses the challenging problem of verifying the adaptability of drill bit cutting tools in the extreme hypothermic environment of the lunar polar regions. An equivalent verification method based on the liquid nitrogen temperature range (–180°C) is proposed to replace the costly experiments in the liquid helium temperature range (20-40 K). By analyzing the influence of extremely low temperature on the mechanical properties of lunar regolith, it is found that the strength characteristics of the frozen soil working condition at ≤ –180 °C are similar to those in an environment of –238 °C, providing a theoretical basis for the equivalent verification. Furthermore, by combining with the variation laws of the mechanical properties of the drill bit cutting tool material (YG6X cemented carbide) in extremely low temperatures, an equivalent verification theory with the impact toughness ratio $\lambda$ as the core criterion is established. It is proposed that the risk of edge chipping in a lower temperature environment can be simulated by proportionally increasing the kinetic energy of the drilling tool (adjusting the rotational speed, feed rate, and impact work by $\lambda$ times) and increasing the external load (such as increasing the rotational torque). The test results show that when $\lambda$ = 1.31 (>1), no edge chipping damage occurs to the drill bit cutting tools in both the –180 °C equivalent test and the –238 °C real environment test, verifying the feasibility of this equivalent method. This method significantly reduces the test cost and provides technical support for the reliability verification of drilling tools in the water ice drilling mission in the lunar polar regions.

## Acknowledgment

This work was financially supported by the National Natural Science Foundation of China (U2013603, 52434004, U21B2072).

## Nomenclature

$E_{k1}$ – initial potential energy of pendulum, [J]
$E_{k2}$ – potential energy after pendulum impact, [J]
$J$ – moment of inertia of the drilling tool, [kgm$^2$]
$K_v$ – impact energy of the material, [J]
$m$ – mass of the feed motion, [kg]
$Q$ – impact energy, [J]
$v$ – feed motion speed, [ms$^{-1}$]

*Greek symbols*

$\lambda$ – ratio of the impact energy of the cutting tool material at –180 °C to that at –238 °C
$\omega$ – rotational speed, [rads$^{-1}$]

## References

[1] Ye, P. J., *et al*., Achievements and Prospect of Chinese Lunar Probes, *Journal of Deep Space Exploration*, *3* (2016), 4, pp.323-333
[2] Wang, C., *et al*., Research Prospects of Lunar Polar Water Ice Resource in Situ Utilization, *Journal of Deep Space Exploration*, *7* (2020), 3, pp. 241-247
[3] Wu, W. R., *et al*., China Lunar Exploration Program, *Journal of Deep Space Exploration*, *6* (2019), 5, pp. 405-416
[4] Watson, K., *et al*., The Behavior of Volatiles on the Lunar Surface, *Journal of Geophysical Research*, *66* (1961), 9, pp. 3033-3045
[5] Yuan, Y, *et al.,* Prospect of Lunar Base Construction Scheme, *Journal of Deep Space Exploration*, *5* (2018), 4, pp. 374-381
[6] He, C. D., *et al*., Research Progress of Lunar Surface Water Ice Detection and Occurrence Form, *Vacuum and Cryogenics*, *27* (2021), 6, pp. 589-600
[7] Vasavada, A.R., *et al*., Near-surface Temperatures on Mercury and the Moon and the Stability of Polar Ice Deposits, *Icarus*, *141* (1999), 2, pp. 179-193
[8] Nozette, S., *et al.*, Integration of Lunar Polar Remote-sensing Data Sets, Evidence for Ice at the Lunar South Pole, *Journal of Geophysical Research Planets*, *106* (2001), E10, pp. 23253-23266
[9] Thomson, B. J., *et al.*, An Upper Limit for Ice in Shack Let on Crater as Revealed by LRO Mini-RF Orbital Radar, *Geophysical Research Letters*, *39* (2012), 14, L14201
[10] Ji, J., *et al*., Simulation of Icy Lunar Regolith and Experiment on Its Shear Strength, *Journal of Deep Space Exploration*, *10* (2023), 2, pp. 199-210
[11] Williams, J. P., *et al.*, Seasonal Polar Temperatures on The Moon, Journal of Geophysical Research, *Planets*, *124* (2019), 10, pp. 2505-2521
[12] Liu, J., *et al*., Analysis and Prediction of Uniaxial Compressive Strength of Icy Lunar Regolith under Extreme Temperature, *Advances in Space Researc*h, *69* (2022), 12, pp. 4391-4407

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