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RESEARCH ARTICLE

Design and Verification of a Novel Sampling System for Lunar Water Ice Exploration

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ABSTRACT Aiming at the problem that it is difficult to collect the subsurface lunar water ice samples quickly due to the cementation-hardening of ice and soil at extremely low temperature in the permanent shadow regions, a novel lunar water ice sampling system is proposed, which uses kinetic energy penetration to efficiently expose the subsurface lunar water ice and uses manipulator to accurately collect and transfer the lunar soil samples. Based on the analysis of the working strategy of the sampling system, an engineering prototype of penetrating modular was designed and developed, and its penetration efficiency was tested based on the principle that the mechanical characteristics are equivalent. The test results show that the penetrating modular can penetrate into the target whose uniaxial compressive strength(UCS) is about 30Mpa (equivalent to the UCS of the simulated lunar water ice) with low power consumption and high efficiency, the penetration depth can reach 234mm, and the penetration time is less than 1s.

INDEX TERMS Lunar exploration, water ice, sampling system, permanent shadow region.

I. INTRODUCTION

Since Watson supposed that water ice may exist in some regions of the Moon in 1961, the exploration of water ice has always been the focus of the lunar exploration [1], [2], [3], [4]. As a conventional detection technology, remote sensing technologies have been widely used in the exploration of the lunar water ice. However, because of the influence of the lunar soil characteristics, such as mineral composition, bedrock distribution, and topographic characteristics, the remote sensing data cannot provide the direct evidence that there is water ice on the Moon [5], [6], and the in-situ detection becomes the most effective and direct technical approach for lunar water ice exploration. United States, Russia, European, and other research organizations have proposed their own in-situ water ice exploration plans in lunar polar regions [7], [8], [9]. China has successfully obtained the lunar soil in the middle latitudes of the Moon, and China will also carry out its own exploration in lunar polar regions to confirm the existence of water ice in the polar region [10], [11], [12].

According to the remote sensing data of the lunar polar regions, the permanent shadow regions(PSR) located at the polar region of the Moon may has the temperature conditions for long-term occurrence of water ice, and the lunar water ice has a high distribution probability at the surface soil and subsurface soil in the PSR [13], [14]. Therefore, to confirm the existence of lunar water ice directly, the surface and the subsurface lunar regolith samples should be collected and analyzed.

Based on investigation and analysis of the subsurface sampling missions at Moon or planets, the subsurface sampling task mainly includes three technical approaches: shoveling-excavating, drilling, and static force penetration, etc. 1) Shoveling or excavating: this approach can gradually expose the subsurface material, layer by layer, at the form of shoveling or excavating, and it is more suitable for the collection of loose soil samples with low density and low cohesion. For example, Chang'E-5 sampling manipulator, Phoenix sampling

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manipulator and Luna-25 sampling manipulator, all adopt the shoveling-excavating method to collect the samples [15], [16], [17]; 2) Drilling sampling: drilling is the main technical approach for deep sampling at present, which has the advantages with mature technology and high reliability, but also has its inherent technical disadvantages, such as large weight and big envelope size, long operation time, high power consumption, and large operation reaction force. Drilling sampling system is generally equipped on the platforms with large weight, and it is very suitable for the collection of samples with higher density and hardness. So, drilling sampling is usually used at the exploration missions that allow long residence time and need to collect the samples located at a high depth. For example, by using drilling sampling method, Chang'E-5 and Luna missions obtained lunar soil samples that the located depth is no less than 1m [18], [19], [20], [21]; and the first mission of Artemis also equipped with a drilling equipment; 3) Static force penetrating: by continuously pressing the soils on the penetrating path, the penetrators with the function of collecting or in-situ detecting can collect or detect the subsurface soil samples. Because the penetration speed is usually very low, the mothed is suitable for long-term and in-situ detection of soil with large porosity and low density. For example, the "Mole" equipped by "Insight" detector is such a detection method [22], [23]. In addition, the penetration or impact techniques are also used in planet or asteroid sampling and exploration missions [24], [25], [26].

However, compared with Apollo, Luna, Chang'E-5 and other missions at the middle or low latitudes of the Moon, the lightless and low-temperature environment conditions of PSR have a great influence on lunar regolith or water ice, and the collection of the lunar regolith samples in PSR will have to face many new difficulties: 1) The detector cannot supplement electric energy due to the lightless conditions, so the sampling and detecting tasks should be carried out under the condition that it should preferentially maintain the survival of the detector platform. That means, the allowed power consumption and sampling time of the sampling system are extremely limited; 2) Different from the aggregation state of dry lunar regolith in the middle and low latitudes, lunar regolith with water ice can be regarded as the mixture of water and lunar soil with different particle size, which may have cementation effect under the low temperature environment; Therefore, the cohesive force, strength and other mechanical properties of lunar water ice are greatly enhanced compared with that of the dry soil in the low latitudes [27], [28], [29], [30]. So it is extremely difficult to obtain subsurface lunar water ice samples.

In view of the above engineering problems and difficulties faced by the sampling and detection task in PSR, a novel sampling system which has low electric energy consumption and high exposure efficiency for subsurface lunar regolith with high hardness is designed in this paper: based on the characteristics that the explosives has high chemical energy density and high energy release efficiency, by using the efficient conversion between the chemical energy and kinetic energy, the rapid exposure of subsurface lunar water ice with high hardness is achieved at the form of the kinetic energy penetration; and a manipulator and sampling tool are used to realize the accurate collection of samples at the side wall and the bottom of the exposed area. The technical approach of the sampling system is different from the technical approaches of the traditional sampling mentioned above in principle, which can effectively solve the problem that it is difficult to collect the lunar regolith or lunar water ice with high-intensity and high hardness at a low electric energy consumption and high sampling efficiency. Considering that the manipulator and sampling tool have a good inheritance in technology, but the kinetic energy penetration technology is the key technology that affect the engineering feasibility of the sampling system, so the paper mainly focuses on the design and verification of the penetrating modular.

II. SAMPLING SYSTEM DESIGN

The novel lunar water ice sampling system proposed in this paper is shown in Fig.1. In this section, we mainly focus on the composition of the sampling system and its own on orbit sampling procedures.

A. GENERAL DESIGN OF THE SAMPLING SYSTEM

The novel in-situ sampling system proposed in this paper is composed of sampling manipulator, sampling effector and the penetrating modular, which can be used to detect, collect, and transfer the subsurface lunar regolith samples.

The penetrating modular is integrated near the elbow joint of the manipulator, which is used to efficiently expose the high hardness lunar regolith or water ice samples that may be encountered during the sample tasks, and rapidly construct an open sample area for the sampling effector. The sampling effector is installed at the end of the sampling manipulator, and has the ability to collect and detect (by using the embedded in-situ sensor [31]) the samples on the exposed area constructed by penetrating modular, and the samples (about 1.5cm^3) can be temporarily stored in the effector. The sampling manipulator can carry the penetrating modular and the effector to collect the samples at different areas and transfer the samples to the scientific equipment to analysis the water content characteristics. In addition, each joint of the manipulator is equipped with an electromagnetic brake, so, when the joints powered off, the brakes can provide braking torque to hold on the posture of the manipulator and maintain the reaction force from the impact of the launch. The braking torque of the joints can be obtained by selecting appropriate brakes according to the reaction force from the impact of the penetrating modular.

B. SAMPLING PROCEDURE DESIGN

According to the composition of the lunar water ice sampling system, the working strategy or sampling procedures of the sampling system can be divided into three steps:

(1) *Exposing the subsurface lunar regolith or water ice to construct an open sampling area for sampling effector.*

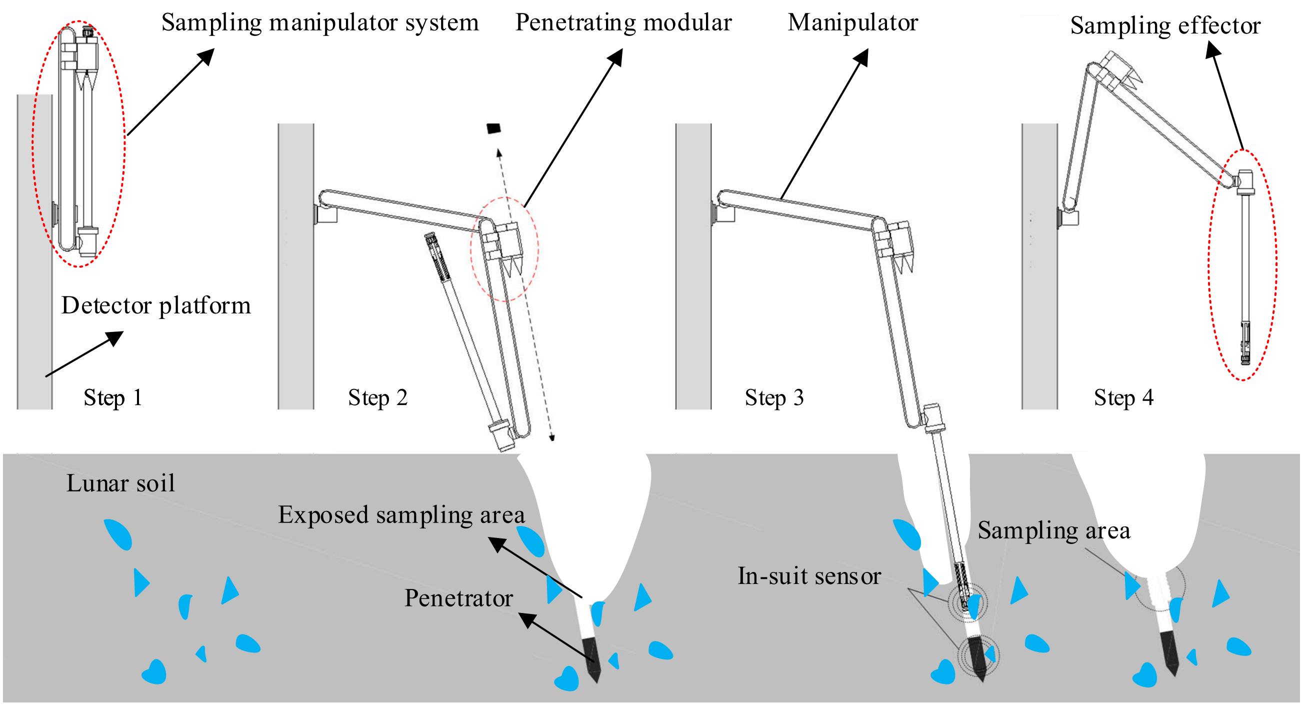

FIGURE 1. The composition of the sampling system and its own on orbit sampling procedures. 1) step 1: The detector moves around to look for high-value sampling areas; 2) step 2: exposing the subsurface lunar regolith or water ice to construct an open sampling area for sampling effector; 3) step 3: Sampling and in-situ detecting at the exposed area; 4) step 4: Transferring the lunar regolith or water ice samples.

The sampling manipulator moves to the target sampling area and touches the Moon ground to support it, then the joints are powered off and be braked to ensure that the sampling manipulator can keep the constructing configuration. And then, when the penetrating modular is activated, the chemical energy stored in penetrating modular will convert into the kinetic energy of the penetrator. The penetrator hits the sampling area at high speed and penetrate into the lunar regolith, by which the subsurface lunar regolith or lunar water ice can be quickly exposed with no electric energy consumption and an open sample area will be constructed. In the design of penetrating modular, the low reaction force design has been considered: when the penetrator shoots at the lunar surface, some structural components of the penetrating modular are separated from the manipulator, and fly away from the detector platform in the opposite direction with the penetrator, so as to minimize the influence of the reaction force of the penetrator on manipulator, which can also reduce the demand for the braking torque of the manipulator joints.

(2) *Sampling and in-situ detecting at the exposed area.* The manipulator powered on, adjusts its configuration and takes the sampling effector to the exposed area or into the penetrated channel; then the effector samples at the exposed surface or the side wall of the penetrated channel constructed by the penetrator, and the lunar soil samples (no more than 1.5cm^3) can be temporarily stored in the effector. Moreover, the sensor integrated inside the sampling effector can carry out in-situ detection.

(3) *Transferring the lunar regolith or water ice samples.* The manipulator powered on and transfer the effector to the sample receiving port of the scientific equipment. Then, the sampling effector releases the collected samples into the scientific equipment; and then, the scientific equipment can accurately analyze that whether the samples contains water ice and other volatile matters.

Based on the analysis of the sampling strategy, it is clear that the penetrating module is the core component of the sampling system, and it is mainly responsible for exposing the subsurface high-intensity lunar regolith samples with low power consumption and high efficiency. Consider that the module directly influences the technical feasibility of the sampling system, this paper mainly focuses on the design and verification of the penetrating modular.

III. PENETRATING SYSTEM DESIGN

A. COMPOSITION OF THE PENETRATING SYSTEM

The penetrating modular is integrated at the manipulator. The penetrating modular mainly consists of the penetrator, the energy storage unit, the firing barrel and other components, as shown in Fig.2. The energy storage unit mainly includes electrical interface, igniter, high-energy explosive, and sealing components; the firing barrel is a high hardness alloy pipe with a carbon fiber reinforced outer layer.

The working process of the penetrating module is that: the initiation current transmitted by electrical interface causes the igniter to ignite; and then, the igniter will detonate the high explosives; the high-pressure gas generated by the burning of the high explosives drive the penetrator to accelerate in the barrel, so as to realize the conversion between chemical energy and kinetic energy; then, the penetrator shoots out of

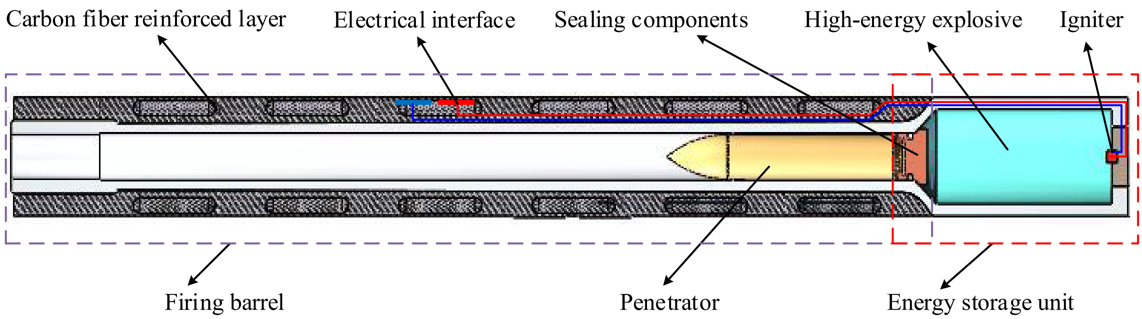

FIGURE 2. The composition of the penetrating modular.

the barrel at a high speed and penetrates into lunar regolith in the sampling area, by which the subsurface high hardness lunar regolith can be exposed efficiently. Since the kinetic energy of penetrator is completely derived from the chemical energy of the high-energy explosive, the electric energy demand of the sampling system can be greatly reduced.

B. PENETRATOR DESIGN

The geometric shape of the penetrator is the main factors that influence its penetrating efficiency. Considering that Conical structure has less resistance in penetration process and can reach a greater penetrating depth than other structures, so the head of the penetrator is designed as a conical structure. Due to the influence of particle size distribution, rock, and other factors, the lunar soil may be anisotropic. Considering that the anisotropy may lead to the deflection of the motion path of the penetrator, which will greatly reduce the penetrating depth and the penetration efficiency. In order to avoid the adverse influence of the subsurface lunar regolith anisotropy on the penetration efficiency, it is necessary to optimize the length-diameter ratio of the penetrator. In this paper, the finite element simulation analysis method is used to analyses the deflection characteristics of the penetrator under the conditions of different length-diameter ratio, and the analysis results are shown in Fig.3.

The analysis results show that the deflection angle decreases with the increase of the length-diameter ratio(LDR), and if the LDR reaches 5, the increase of the LDR will have little effect on the deflection angle, but will have significant effect on the layout and the weight of the penetrator, so the LDR of the penetrator is determined to be 5. In order to ensure that the penetrator has no deformation failure or structural decomposition when it penetrates into the lunar regolith with high hardness, nickel tungsten alloy with high-strength, high-toughness, and high-density is selected as the material of the penetrator. Considering the size matching between the penetrator and the sampling effector, the diameter of the penetrator is determined to be 15mm, and the length is determined to be 85mm.

C. ENERGY STORAGE UNIT DESIGN

The energy storage unit is mainly composed of electrical interface, igniter, high-energy explosive, sealing components and other components. As the energy module of the sampling system, the design of the energy storage unit should consider the following key requirements: 1) The energy storage unit should have enough energy to provide enough kinetic energy for the penetrator; 2) Explosives should have high energy density to reduce the dosage of explosives and the weight of energy storage unit; 3) The energy storage unit should have high reliability to ensure that there is no accidental ignition during the whole task.

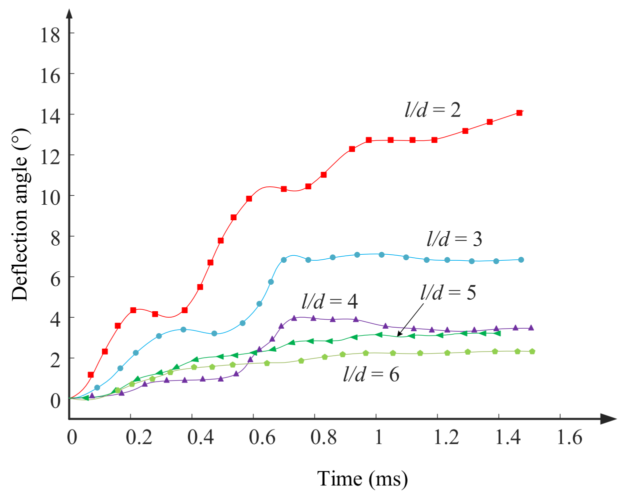

FIGURE 3. Analysis of the penetration characteristic with different length-diameter ratio.

In view of the above key requirements, this paper selects insensitive explosives with high burning rate and high explosive force as the explosive of the energy storage unit. The main components and performance parameters of the explosive are shown in Tab.1 and Tab.2 respectively.

TABLE 1. The main components of the explosive.

Nitrocellulose	Nitroglycerin	Other additives
63.5±2%	34±2%	3%

During the work of the penetrating modular, the chemical energy of the explosives is converted into the kinetic energy of the penetrator and the internal energy of the penetrating

TABLE 2. The performance parameters of the explosive.

Parameters items	Parameters values
Impetus	1191 kJ/kg
Constant volume explosion heat	4870.66 kJ/kg
Constant volume explosion temperature	3671 K
Specific heat	857.41 L/kg
Average molecular mass of the gas	26.14
Ratio of specific heat capacity	1.2138

modular. Therefore, the dosage of explosives filled in the energy storage unit is the most important factor which may greatly influence the penetrating velocity of the penetrator. According to the internal ballistic motion characteristics of the penetrator, the relationship between the time t and the velocity v of the penetrator can be expressed as formula (1), and the relationship between the movement distance L and the velocity v of the penetrator in the firing barrel can be expressed as formula (2).

$$\int_0^t \frac{SP}{\varphi m} \mathrm{d}t = v \tag{1}$$

$$\int_0^t v \mathrm{d}t = L \tag{2}$$

where: S is the internal cavity area of the firing barrel, P is the bore pressure of the firing barrel, m is the mass of the penetrator, φ is the mass correction coefficient of the penetrator, selecting 1∼1.3; t is the time of the combustion; v is the instantaneous velocity of the penetrator.

Obviously, the bore pressure of the firing barrel is mainly related to the dosage of explosives. In this paper, based on the empirical formula of interior ballistic calculation and the basic equation of gas state transformation, the basic ballistics equation of the penetrating system is established, as shown in formula (3). Based on the (1), (2), and (3), the formula (4) can be obtained.

$$SP(t)\left(L_{\varphi} + L(t)\right) = f\omega\psi(t) - \frac{k-1}{2}\varphi m v^2(t) \tag{3}$$

$$\varphi m \frac{dv(t)}{dt}\left(L_{\varphi} + \int_0^t v(t)\,\mathrm{d}t\right) = fw\psi(t) - \frac{\theta}{2}\varphi m v^2(t) \tag{4}$$

where: $L_{\varphi} = L_0\left[1 - \frac{\Delta}{\delta_m} - \Delta\left(\alpha - \frac{1}{\delta_m}\right)\right]\psi$, $L\varphi$ is the length of the free volume of the explosive chamber, L_0 is the length of acceleration distance, f is the impetus, ω is the dosage of explosives, k is the gas adiabatic coefficient, Δ is the filling density, δ_{m} is the density of the explosives, α is the residual capacity of combustion chamber, Ψ is the charging coefficients of the explosives.

By using the fourth-order Runge-Kutta method iterative algorithm, the internal ballistic characteristic curves of the penetrating module can be obtained, as shown in Fig.4.

According to the internal ballistic characteristic curves, when the movement distance of the penetrator in the firing barrel is about 200mm and the dosage of explosives is about 24g, the speed of the penetrator can reach 350m/s based on the design of the penetrating module in this paper.

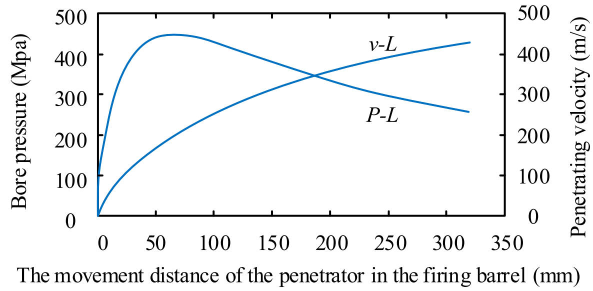

FIGURE 4. Internal ballistic characteristic curves of penetration unit.

D. FIRING BARREL DESIGN

The firing barrel is the main structure of the whole modular. During the penetrating operation, a closed cavity can be formed by the firing barrel and the sealing components; and the high-pressure gas generated by the combustion of the explosives drives the sealing components and the penetrator to accelerate in the firing barrel. In order to ensure that the firing barrel can reliably bear the high-pressure and has a relatively light weight, the inner layer of the firing barrel is made of ultra-high strength steel (40CrNi2SiMoVA), and the outer layer is coated with carbon fiber.

E. PENETRATION DEPTH ANALYSIS

The penetration depth is a key index for the design of penetrating modular. Based on the design parameters of penetrating modular, the penetration depth is analyzed in this paper. According to the classical terminal ballistics theory, Forrestal formula can be used to calculate the penetration depth for penetrators with low mass.

$$d_{\mathrm{p}} = \frac{m}{2\pi D^2 \rho N} \ln\left(1 + \frac{N\rho V^2}{K f_{\mathrm{c}}}\right) \tag{5}$$

where: d_{p} is the penetration depth; m is the weight of the penetrator; D is the diameter of the penetrator; ρ is the target density; N is the shape coefficient of the penetrator; V is the penetration velocity; K is the target strength coefficient; f_c is the UCS of the target. According to Mohr-Coulomb yield criterion, the relationship between K and f_c can be expressed as (6) approximately.

$$S = 82.6\left(f_{\mathrm{c}}/10^6\right)^{-0.544} \tag{6}$$

According to Formula (5) and Formula (6), assuming that the penetration speed is 350m/s, the penetration depth of the penetrator to lunar soil with different UCS is shown in Fig.5. From the relationship curve between the penetration depth and the UCS, it can be seen that when the UCS of lunar soil water ice does not exceed 30Mpa, the penetration depth of the penetrating modular designed in this paper can reach about 187mm, which can better reach the design goal

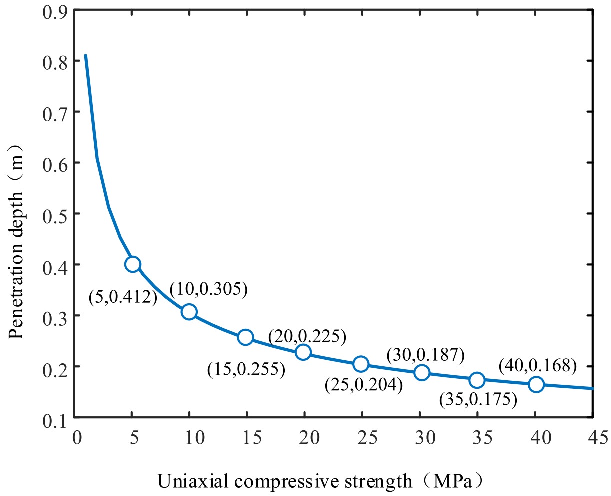

FIGURE 5. Penetration depth of lunar water ice with different UCS.

of efficiently exposing the subsurface lunar soil samples with high hardness.

IV. EXPERIMENTAL VERIFICATION

A. DEVELOPMENT OF ENGINEERING PROTOTYPES

In order to verify the design rationality and engineering feasibility of the penetrating modular, three engineering prototypes are developed based on the design parameters, and the penetration tests are carried out. The engineering prototype of penetrating modular before coating the outer layer with carbon is shown in Fig. 6.

FIGURE 6. Engineering prototype of penetrating system before coating the outer layer with carbon fiber.

B. THE MECHANICAL PROPERTIES RESEARCH AND EXPERIMENT OF SIMULATED LUNAR WATER ICE

Since mechanical properties of the lunar water ice are the key characteristics that influence the sampling operation, and also the decisive factors that directly influence the penetration efficiency of the penetrator, so the mechanical properties of the lunar water ice are researched in the paper to carry out the feasibility experiment of the penetrating modular.

Different from the aggregation state of dry lunar soil at middle and low latitudes, lunar water ice can be regarded as a mixture of water and dry lunar soil with different particles size, and it may have an ice-soil cementation effect under the conditions of extreme low temperature in the PSR, so the mechanical properties of the lunar water ice will be greatly enhanced compared with dry lunar regolith. Generally, the compression failure resistance of lunar water ice can be characterized by its UCS. The UCS of the lunar water ice is mainly influenced by the mineral composition, particle size, compactness, water content, and temperature.

In order to obtain the mechanical properties of the lunar water ice more accurately, and to verify the performance of the penetrating modular, according to the characteristics of lunar soil mineral composition in the polar regions of the Moon, anorthosite and basalt are used to simulate the lunar soil in this paper, and the simulated lunar soil was used to prepare the simulated lunar water ice samples with different temperature conditions and different water content. By using the prepared simulated lunar water ice samples, experimental test on the UCS of the samples is carried out, and the test process is shown in Fig7.

FIGURE 7. UCS test of simulated lunar water ice with different moisture content and at different temperature.

In order to obtain the UCS boundary data of the sample, the compactness of simulated lunar soil used in the test is 99%. and the specific parameters of simulated lunar water ice samples are shown in Table 3.

TABLE 3. Parameters of the simulated lunar water ice.

Indicator items	parameter
Mineral composition	Anorthosite(70%) and basalt(30%)
Particle size	≤ 1mm
Compactness	99%
Moisture content	5%, 10%, 16%
Temperature	40K, 80K

During the UCS test, the simulated lunar water ice showed brittle failure at a low temperature conditions. The UCS test results are shown in Fig8.

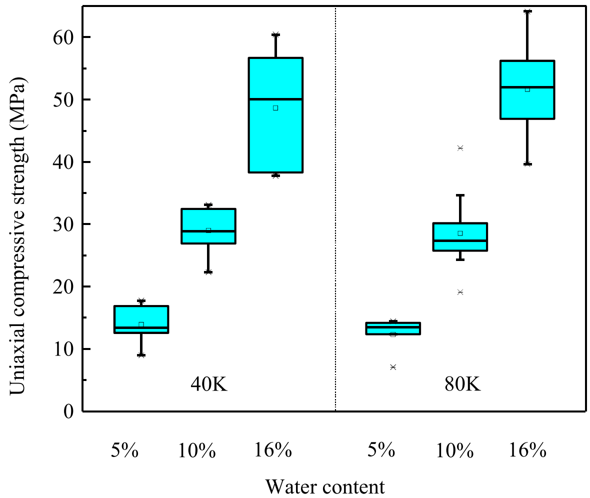

FIGURE 8. UCS test results of simulated lunar water ice with different moisture content and at different temperature.

From the test results, it can be seen that: 1) at the same temperature, the UCS of samples with different water content is significantly different, and it increase with the increase of the water content; 2) The UCS of simulated lunar water ice generally increases with the temperature decrease, but when the temperature is lower than 100K, the influence of temperature on the UCS of lunar water ice will gradually decreases, and the UCS of simulated lunar water ice at 40K and 80K is basically equivalent. The experimental results of simulated lunar water ice in this paper are consistent with results of foreign scientific research institutions. Considering that the LCROSS mission analysis and predict that the water content is about 5.6±2.9%, the paper selects the mechanical properties of simulated lunar water ice with 10wt% water content as the experimental reference value of the penetrating modular, and the UCS of the experimental targets use in the penetrating tests is about 30Mpa.

C. MECHANICAL PROPERTIES OF THE PENETRATING TARGET

According to the research of lunar water ice mechanical properties, the UCS of the lunar water ice are related to the temperature. When the UCS of the simulated lunar water ice is 30Mpa, the environment temperature is required to be as lower as 40K. As the penetration test of the penetrator needs to be carried out in a large space, it is extremely difficult to build a low temperature environment of 40K in a large space. Considering that the penetration performance is mainly influenced by the mechanical properties of the simulated lunar soil, this paper uses the target which has the same UCS as the simulated lunar water ice to carry out the penetration test, which can overcome the influence of the environment temperature on the test.

In this paper, the concrete materials is used to replace the extremely low temperature simulated lunar water ice. In order to ensure the accuracy of the equivalent mechanical properties, three standard samples were prepared and the UCS of the samples were tested. The UCS tests of concrete materials is shown in Fig.9, and the test results are shown in Table.4. The average UCS is about 31.98Mpa, which is equivalent to the UCS of the simulated lunar water ice.

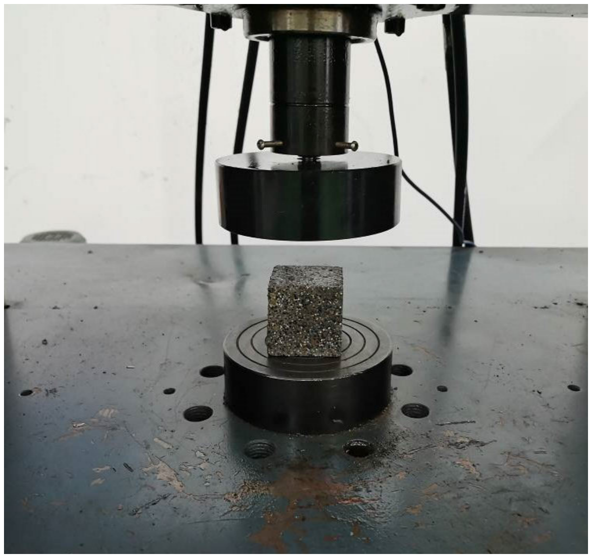

FIGURE 9. The mechanical properties test of the concrete materials.

TABLE 4. USC test data of the penetrating target.

NO.	Pressure	Value of the UCS
1	77.966 kN	31.198 MPa
2	82.990 kN	33.196 MPa
3	78.842 kN	31.537 MPa

D. PENETRATING TEST BASED ON THE EQUIVALENT TARGET

Three times penetrating tests based on the equivalent target were carried out to verify the performance of the penetrating modular. The target states after the test are shown in Fig.10, and the actual working parameters of the penetrating system are shown in Table.5. The test results show that: 1) when the actual dosage of the explosives is 28g, the actual penetrating velocity of the penetrator can reach 353.13m/s, which can accord with the designed value 350m/s; 2) The maximum actual penetrating depth of the penetrator is about 234mm, and it is greater than the theoretical penetrating depth analyzed in the paper, which is mainly caused by that the actual dosage of explosives 28g is more than the designed dosage of explosives 24g; 3) The structure of the penetrator and the firing barrel is undamaged, and the penetrating modular commendably meets the design requirements and can rapidly exposure the subsurface lunar water ice; 4) All the surface of concrete target shows brittle fracture, and the exposing area is about 147mm × 130mm.

(a) target state for the first test (b) target state for the second test (c) target state for the third test

FIGURE 10. The penetrating tests of the penetrating modular and The target states after the penetrating tests.

TABLE 5. Test data of the penetrating system.

NO.	agent mass	penetrator mass	penetrating velocity	penetrating depth	penetrating time	reaction force	fracture area size
#1	28 g	226.5 g	353.13 m/s	234 mm	<1 s	<150 N	147 mm×130 mm
#2	26 g	226.5 g	343.42 m/s	227 mm	<1 s	<150 N	145 mm×105 mm
#3	26 g	226.5 g	346.83 m/s	219 mm	<1 s	<150 N	170 mm×120 mm

V. CONCLUSION

In this paper, a novel sampling system for lunar water ice exploration in permanent shadow regions is proposed. The sampling system can rapidly expose the subsurface high hardness lunar regolith or lunar water ice with extremely low power consumption at the form of kinetic energy penetration, which is different from the existing subsurface lunar soil exposure technologies in principle, such as shoveling and drilling. Based on the experimental study on the mechanical properties of simulated lunar water ice in low temperature environment, the penetration efficiency of the penetrating module was tested and verified with the principle of the mechanical properties equivalence. The test results showed that: without consuming the electrical power consumption of the detector, the sampling system penetration module can achieve rapid penetration to the equivalent target of the simulated lunar soil water ice with the UCS no less than 30Mpa; the surface of the exposed area is up to 147mm $\times$ 130mm; the penetration depth is no less than 234mm, and the time is less than 1s. The research result shows that the penetrating modular proposed in the paper has a good technical feasibility for the mission of the lunar water ice sampling exploration in PSR, and it can effectively solve the efficiency and the high energy consumption problems faced by the existing sampling technologies.

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