Shear Properties of Lunar Regolith Simulants

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Abstract

The accuracy of lunar regolith simulants for lunar drilling and sampling is mainly based on their particle shape and grain size distribution. To determine the grain-size distribution and shear strength parameters, grain-size distribution tests and conventional tri-axial compression experiments were conducted on the lunar regolith simulants. A new sample preparation apparatus was designed to obtain the shear strength of lunar regolith simulants under high and low confining pressures respectively. Grain-size distribution, cohesion and friction angle of lunar regolith simulants in this paper were compared with lunar regolith and other simulants to illustrate that the strength parameters of the lunar regolith simulants can be applied to the development of lunar drilling and sampling apparatus and other lunar engineering applications.

Keywords: Lunar Regolith Simulant; Grain-size Distribution; Tri-axial Compression Experiment; Shear Strength

1. Introduction

It is always thought that the surface of the moon is soft for its low gravity, while the fact is that the main region on lunar surface is relatively firm, and only impact crater rims and their vicinities are locations where soft and unconsolidated regolith exists in abundance\textsuperscript{[1]}.

The US extensively measured the in-situ properties of lunar surface and lunar soil under the surface during the Apollo era, and Lunar, Surveyor and Apollo mission brought back 381.7kg lunar regolith\textsuperscript{[2]}. The 0.1g precious lunar regolith in China which was gifted from America is not nearly enough to conduct experiments to study its geotechnical properties\textsuperscript{[3]}. Even for America, only the physical and chemical properties as well as some limited
geotechnical behaviors of lunar regolith samples were tested, which could not suffice the demand for the complete lunar soil mechanical research at all. Therefore, scientists have prepared substitute materials on earth as the simulant for real lunar regolith based on the limited data. The great amount of lunar regolith simulant can be applied to the research and engineering of future lunar operations, such as spacecraft landing, construction, mining and foundation design, all of which need its accurate geotechnical properties. Testing the mechanical properties of lunar regolith simulants seems to be of increasing significance.

2. Analysis on Grain-size Distribution

2.1. Experimental Procedures

Grain-size distribution test for lunar regolith simulant was conducted at the basis of specification for soil test SL237-006-1999[4]. Sieving method is for samples whose grain sizes larger than 0.075mm, and densimeter method is for those whose grain sizes smaller than 0.075mm.

Coarse sieving was neglected as the samples whose grain size larger than 2mm is 1.5/502.2=0.29%, which is smaller than 10%. The samples were poured into fine sieves with openings of 2.0, 1.0, 0.5, 0.25, 0.1, 0.075mm which were placed from top to bottom and vibrated by the vibrating screen for 10 to 15 minutes. And then, samples on each sieve were weighted and recorded.

The samples whose grain sizes smaller than 0.075mm is 319.7/502.2=63.7%, greater than 10%, thus needed to be analyzed by soil densimeter TM-85. Lunar regolith simulants of 30g and water of 200ml were poured into a conical flask which was then heated on a sand bath. After boiling for an hour, the liquid was cooled firstly, and then washed and screened through a washing screen whose opening diameter is 0.075mm until the suspension was limpid. A total amount of 1000ml suspension under washing screen and pure water were poured into the graduate cylinder later, and the soil densitometer readings were recorded when the suspension settled for 30s, 1min, 2min, 5min, 15min, 30min, 1h, 2h and 24h respectively.

2.2. Experimental Results

According to the statistics from grain-size distribution analysis of lunar regolith simulants, the sample loss before and after the experiment on fine sieves is (500.5-500.2)/500.5=0.06%, less than 1%, conforming with the regulation of SL237-006-1999.

The cumulative percent less than the certain grain sizes resulted from the sieving method and the densimeter method were calculated unitedly to obtain the grain-size distribution curve of the lunar regolith simulant herein[5], as shown in Fig.1. Tab. 1 shows the grain gradation index.
3. Tri-axial Compression Test

3.1 Sample Preparation

The samples for triaxial compression test were cylindrical[6-7], 37.1mm in diameter and 80mm in height. Typically, triaxial samples should be prepared with a three-part mold and then moved to the pressure chamber, however, the conventional mold is not suitable for the lunar soil simulant as its special physical properties. Thus, a new mold for sample preparation of lunar regolith simulants was designed and the samples were prepared directly on the base of the tri-axial pressure chamber. The new mold contains two segments and two pairs of garter springs (see fig. 2a, b) with an inner diameter of 39.1mm, a thickness of 5mm and a height of 130mm. A vent was opened in the center of one segment of the mold to exhaust air between the mold and the rubber membrane during sample preparation process to avoid sample deformation. Rubber strips were filled in the groove carved on the contacted plane of the two halves of the mold to prevent air leak[8-9]. Sample preparation process was also modified as follows:

Table 1. Key Parameters of the Particle-Size Distribution Curve

| Effective size 10% | \(d_{10}(\text{mm})\) | 0.012 |
|--------------------|----------------------|------|
| Particle size such that 30% of the particles is smaller | \(d_{30}(\text{mm})\) | 0.028 |
| Particle size such that 60% of the particles is smaller | \(d_{60}(\text{mm})\) | 0.069 |
| Coefficient of uniformity | \(C_u = \frac{d_{60}}{d_{10}}\) | 5.75 |
| Coefficient of curvature | \(C_z = \frac{d_{30}}{d_{60} \cdot d_{10}}\) | 0.95 |

Fig. 2 (a) Three View of the New Mold; (b) Top and Front View of the Spring Garters

1) Two halves of the mold and two pairs of spring garters were assembled firstly, inside which a tubular rubber membrane with a diameter of 39.1mm covered, and the upper part of the rubber membrane that beyond the mold was turned down. The air between the rubber membrane and the mold inner wall was extracted by a water ball to make them cling together.

2) A porous stone and filter paper were put on the base of the pressure chamber, on which the mold was then fixed. And the spring garters were screwed to tighten and stabilize the mold.
(3) The height from the filter paper at the bottom to the top of the mold was measured by a vernier caliper. Each group of sample was 163.1 g in weight with a controlled density of 1.698 g/cm$^3$ and then quartered. Each quarter of samples were poured and impacted successively to the height of 20 mm inside the mold and scarified between layers.

(4) A porous stone, filter paper, and sample cap were put in turn on the top layer of the sample, and the upper part of the rubber membrane that beyond the mold was then turned up.

(5) Subsequently, the mold was dismantled. The upper part of the rubber membrane was fastened with the sample cap and the lower part was fastened with the base, during which a split mold was used to avoid the disturbulance of the sample.

3.2 Experimental Procedures

The tri-axial testing system consists of a pressure chamber, axial compression and measurement frame, and confining pressure system.

Triaxial compression tests were conducted inside the pressure chamber with a shear rate of 0.8 mm/min under the strain-controlled loading mold. Readings of dynameter and axial deformation were recorded each time when the sample deformed 0.3% to 0.4% or 0.2 mm axially as well as when it deformed 0.7% to 0.8% or 0.5 mm axially if the axial deformation was larger than 3%, during which the confining pressure were controlled to 10 kPa, 20 kPa, 30 kPa, 40 kPa, 50 kPa, 100 kPa, 200 kPa and 300 kPa to study the strength properties of the lunar regolith simulants under high and low pressures.

3.3 Results Analysis

There are two methods to obtain the shear strength parameters, one is the common tangent of Mohr circles, the failure envelope, which determines the cohesion $c$ and friction coefficient $f$ by the slope and intercept of the failure envelope directly; the other is the mean line of failure stress points, the strength envelope, which determines the cohesion $c$ and friction coefficient $f$ by the angle $\alpha$ and intercept $\alpha$ of the strength envelope indirectly. Two least squares fitting methods were used to obtain the accurate value of cohesion and inner friction angles (see fig. 3).

![Fig. 3. Graphics for Calculating Shear Strength Parameters of Lunar Regolith Simulants](image)

The p-q method is based on the fitting of failure stress points:

$$q = a + p \tan \alpha$$  \hspace{1cm}  (1)

$$f = \tan \varphi = \tan(\arcsin(\tan \alpha))$$  \hspace{1cm}  (2)

$$c = \frac{a}{\cos \varphi} = \frac{a}{\cos(\arcsin(\tan \alpha))}$$

where $q$ is $(\sigma_1 - \sigma_3)/2$ and $p$ is $(\sigma_1 + \sigma_3)/2$

The $\sigma_1, \sigma_3$ method is based on the fitting of major and minor principal stresses:

$$\sigma_1 = 2 \tan \left( \frac{\varphi + \pi}{4} \right) + \sigma_3 \tan \left( \frac{\varphi}{2} + \frac{\pi}{4} \right) = A + B \sigma_3$$  \hspace{1cm}  (3)
\[
\begin{align*}
\begin{cases}
    f = \tan \varphi = \tan(2 \arctan B^{0.5} - \frac{\pi}{2}) \\
    c = \frac{A}{2 \tan \left(\frac{\varphi}{2} + \frac{\pi}{4}\right)} = \frac{A}{2B^{0.5}}
\end{cases}
\end{align*}
\]  

(4)

Where A and B are the slope and intercept of the failure envelope respectively.

Mohr circles and their common tangent of lunar regolith simulants were drawn according to the triaxial testing results (see tab. 2), as shown in fig. 4 and fig. 5. The shear strength parameters of lunar regolith simulants were determined by the two methods mentioned above.

When the confining pressure ranging from 10kPa to 30kPa, cohesion and friction angle of lunar regolith simulants herein are \(c=10.02\text{kPa}\) and \(\varphi=44.42^\circ\) by p-q method, and \(c=10.03\text{kPa},\ \varphi=44.48^\circ\) by \(\sigma_3-\sigma_1\) method. Obviously, results of the two methods are similar, therefore, lunar regolith simulants' cohesion is 10kPa, friction angle is 44° under low confining pressure.

When the confining pressure ranging from 50kPa to 300kPa, cohesion and friction angle of lunar regolith simulants herein are \(c=19.77\text{kPa}\) and \(\varphi=53.97^\circ\) by p-q method, and \(c=20.04\text{kPa},\ \varphi=54.02^\circ\) by \(\sigma_3-\sigma_1\) method. Obviously, results of the two methods are similar, therefore, lunar regolith simulants' cohesion is 20kPa, inner friction angle is 54° under high confining pressure.

| \(\sigma_3/\text{kPa}\) | \(\sigma_1/\text{kPa}\) | \(\varepsilon_1/%\) | \(p/\text{kPa}\) | \(q/\text{kPa}\) |
|---|---|---|---|---|
| 10 | 104.9 | 3.75 | 57.5 | 47.5 |
| 20 | 159.8 | 4.75 | 89.9 | 69.9 |
| 30 | 218.1 | 3.75 | 124.1 | 94.1 |
| 50 | 569.4 | 3.75 | 309.7 | 259.7 |
| 100 | 1077.0 | 4.38 | 588.5 | 488.5 |
| 200 | 2058.1 | 5.63 | 1129.0 | 929.0 |
| 300 | 2927.2 | 6.25 | 1613.6 | 1313.6 |

Table 2. Triaxial Test Results

The results above indicate that confining pressure has a relatively obvious influence on the strength parameter of lunar regolith simulants: the value of cohesion and friction angle under confining pressure 50-300kPa is higher than that under confining pressure 10-30kPa.

The relationship curve of deviatoric stress and axial strain for different levels of confining pressures are shown in fig. 6 and fig. 7.
Lunar regolith simulants at each level of confining pressures of 10-30 kPa all arrive at their peak stresses when the axial stains are about 3.75%, and then shear strengths of lunar regolith simulants decrease rapidly as the axial deformations increase and tend to be stable at axial stains of 5.5%, illustrating the existence of residual strengths. While under confining pressure of 50-300 kPa, each sample fails abruptly and has an obvious fractured plane.

It is clear that no matter under high or low confining pressure, lunar regolith simulants’ peak stresses increase as the increase of confining pressures. The axial strains corresponding to different peak stresses are similar under low pressures. The axial strains increase as their corresponding peak stresses increase under high pressures. Thus, the increased confining pressures strengthen lunar regolith simulants’ shear properties.
Fig. 8. Grain-size Distribution Curve Comparison of Lunar Regolith Simulant with Lunar Regolith and Other Simulants

Table 3. Comparison of Lunar Regolith Simulant Herein with Other Simulants

|                  | JSC-1 | CAS-1 | TJ-1 | Lunar regolith simulant herein |
|------------------|-------|-------|------|-------------------------------|
| $C_u$            | 7.5   | 7.9   | 21.5 | 5.75                          |
| $C_c$            | 1.12  | 0.9   | 0.95 |                               |
| Specified gravity |       |       |      |                               |
| Willman et al.(1995) | 2.91  | 2.74  | 2.72 | 2.74                          |

| Shear strength                                                                 |
|-------------------------------------------------------------------------------|
| Perkins and Madson(1996)                                                     |
| ---                                                                           |
| $\rho$                         | $\phi$ | $c$   |
| 1.5                            | 45     | ≤1    |
| 1.6                            | 45     | ≤1    |
| 1.65                           | 45     | ≤1    |
| Perkins et al.(1991)           |
| 1.9                            | 49     | 0.2   |
| Carrier et al.(1991)           |
| 1.62                           | 44.4   | 3.9   |
| Klosky et al.(1996)            |
| 1.72                           | 52.7   | 13.4  |
| Klosky et al.(1996)            |

4. Comparison with Lunar Regolith and Other Simulants

The comparison of grain size distribution curves (see fig. 8) shows that the grain distribution of lunar regolith simulants herein is located between the upper and lower limits of real lunar regolith. The content of lunar regolith simulants whose grain size larger than 2mm is very low; the grain-size distribution of lunar regolith simulants whose grain size ranging from 0.075mm to 2mm is close to the upper limit of real lunar regolith; the grain-size distribution of lunar regolith simulants whose grain size ranging from 0.01mm to 0.075mm is located in the middle of the upper and lower limits of real lunar regolith; also fine grains of the simulants whose sizes smaller than 0.075mm exist.

Tab. 3 shows that the friction angles and cohesion of JSC-1 are 44.4-64° and 0.2-13.4kPa respectively; the friction angles and cohesion of CAS-1 are 33.3-41.8° and 0-12 kPa respectively; the friction angles and cohesion of TJ-1 are 47.6° and 0.86kPa respectively. The comparison of the physical and mechanical properties of lunar regolith simulants herein and other kinds of lunar regolith simulants presents that the strength parameter of lunar regolith simulants herein is similar to that of JSC-1 with the similar density of 1.7g/cm³, and the cohesion of lunar regolith simulants herein is larger than that of CAS-1 and TJ-1. Thus, the lunar regolith simulant in this paper can be used to provide valid shear strength parameter for the design of lunar drilling and sampling apparatus and other lunar engineering applications.

5. Conclusions

Grain-size distribution analysis were conducted to compare the grain-size distribution of the lunar regolith simulant herein with that of the real lunar soils, which illustrated that the lunar regolith simulants with grain size ranged from 2mm to 0.075mm were located between the upper and lower limits of lunar regolith, but the former contains more fine particles.

A new-designed mold was used to prepare the sample of lunar regolith simulants, on which both high and low pressures were applied during the tri-axial compression tests. Test results show that the cohesion and friction angle of the lunar regolith simulant are 10kPa and 44° respectively at low confining pressures of 10kPa, 20kPa and 30kPa; while under high confining pressures of 50kPa, 100kPa, 200kPa and 300kPa, the cohesion and friction angle of the
lunar regolith simulants are 20kPa and 54° respectively. Hence, it is concluded that the confining pressure plays a significant role in the shear properties of lunar regolith simulants whose cohesion and friction angle under high pressures are larger than that under low pressures. The shear strength parameters at low pressures can be applied as references to the study of drilling and sampling test on lunar regolith simulants.

The shear strength parameters of lunar regolith simulants were compared with that of the real lunar soil and other simulants, which presents that the shear strength of lunar regolith simulants herein are most similar with JSC-1 at the similar density of 1.7g/cm³ under low pressures, but larger than others in cohesion. Hence, grain-size distribution, confining pressure and density are all possible factors that cause the difference of the shear strength of lunar regolith simulants. The lunar regolith simulants herein contains more fine particles than others, which might be the main reason that leads to the relatively large cohesion. While the sampling apparatus designed at the basis of larger shear strength parameters will be a better choice for the lunar sampling at the premise of controlling the cost.

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