Research Article

Analysis of the Direct Shear Test and Microstructure of the Lunar Soil Simulant Solidified by Sodium Silicate

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1. Introduction

Lunar soil contains a large amount of He-3, which can be used as a clean energy for long-term human use [1, 2]. In addition, there are plenty of minerals on the moon, which includes orthopyroxene, plagioclase, olivine, and clinopyroxene [3]. Therefore, the exploration of lunar resources has become the focus of competition among countries. Lunar base construction has been put forward by the National Aeronautics and Space Administration (NASA), which is an important goal of human scientific research [4–7]. NASA plans to build human presence in the lunar outpost (habitat) by 2040. China successfully launched Chang’e 5 and retrieved about 2 kg of lunar soil on the lunar surface; lunar base construction is the next step of China’s lunar exploration [8, 9]. In other words, the lunar base not only serves as an energy development base but also as a deep-space exploration relay station [10].

The establishment of the lunar base requires a lot of building materials, and it is too expensive to transport from the Earth to the moon[11, 12]. So the in situ resource utilization of the moon is extremely vital [13]. Lunar soil is the most easily available material on the moon, and it is necessary to effectively use lunar soil resources [14–16].

In order to make better use of lunar soil materials, due to the lack of real lunar soil, a large number of studies on the shear properties of lunar soil simulants have been carried out by domestic and foreign scholars [17, 18]. Changyu Li et al. used raw materials as black volcanic slag and basalt to simulate lunar soil, named as NEU-1 simulated lunar soil [19]. Ryu et al. developed the KLS-1 simulated lunar soil material, which uses intrusive basalt as raw material, and the
chemical composition having high similarity to those of real lunar soil [20]. Lin et al. conducted static triaxial tests on the TJ-1 lunar soil simulant and obtained relevant macroscopic parameters of lunar soil simulant under different relative density, shear rate, and confining pressure [21]. Zhang et al. used PFC3D to numerically simulate the lunar soil, calibrated the mesoscopic parameters of the shear strength of the lunar soil simulant, and obtained the constitutive model of the lunar soil simulant [22]. Mehmet et al. conducted static simple shear tests to find that various basic parameters such as average particle size, uniformity coefficient, and fine powder content affect shear strength [23]. Thannasi et al. studied the shear strength parameters, stress-strain relationships, and volume-change behavior of lunar highlands soil simulators (LSS-ISAC-1) [24]. However, the strength of real lunar soil is relatively low. To produce lunar construction materials from lunar soil, it is necessary to solidify the lunar soil to a certain extent.

At present, the lunar soil geopolymer is a relatively common method to solidify the lunar soil, that is, the use of an alkali activator to fully stimulate the activity of the lunar soil, thereby increasing its strength [25]. Geopolymer is an inorganic polymer formed from silico-alumina materials under the action of an alkali activator [26]. It has good mechanical properties and durability under extreme conditions [27, 28]. Lunar soil is a typical silicon-aluminum material because of its high silicon-aluminum content [29]. Neves et al. studied the activity of the JSC-1A lunar soil simulant, which was similar to real lunar soil samples brought back by the Apollo missions. The study had shown that the thinner JSC-1A material was more active and could be used as a cementing material, while the thicker part of JSC-1A could be used as a filling aggregate, and the JSC-1A could be a potential construction material on the moon [30]. In addition, A.R. Hendrix found that there were water ice resources in the lunar polar regions [31], so lunar soil geopolymers could be used to produce building materials [32]. Pilehvar et al. used DNA-1 lunar regolith to solidify geopolymers in simulated conditions at 80°C for 6 hours, followed by freeze-thaw cycles at −80°C and 80°C. After the freeze-thaw cycle, the addition of urea improves the strength of geopolymer [33]. Alexiadis et al. used a mixed solution of K₂SiO₃ and NaOH to activate the lunar soil simulant and studied the mechanical properties of the lunar soil simulant [34]. Montes et al. used the JSC-1A lunar soil simulant to prepare a geopolymer, tested its compressive strength, and performed a radiation simulation, which could meet the requirements of manned missions to the moon [35]. Wang used volcanic ash to simulate lunar soil materials and studied the compressive strength of lunar soil simulant geopolymers under different alkaline stimulators [36]. In summary, the existing researches on lunar soil simulant geopolymers mostly focused on the study of compressive strength, which did not take into account the actual amount of water resources on the moon, and there were few related studies on its shear strength characteristics.

In view of these, this paper used basalt as the raw material for the lunar soil simulant and proposed to reinforce the lunar soil simulant with sodium silicate (the moisture content was 7.5%). As an alkali activator, sodium silicate can effectively improve the compressive strength of the simulated lunar soil, and the simulated lunar soil geopolymers excited by sodium silicate can still maintain good mechanical properties in extreme environments. The direct shear test, SEM (scanning electron microscope), and XRD microscopic test were carried out to study the evolution of parameters such as shear strength, cohesion, internal friction angle, shear deformation modulus, and direct shear energy dissipation with the variation of sodium silicate solidified lunar soil simulant.

2. Materials and Methods

2.1. Sample Preparation. The experiment uses a kind of basalt with chemical composition similar to real lunar soil as the research object. The material was taken from the alkaline granular basalt in Liuhe District, Nanjing, with macroscopic appearance as shown in Figure 1. Its chemical composition and mineral composition are similar to those of lunar soil in the lunar sea area [37]. The main chemical components are shown in Table 1. Scanning through the electron microscope could find that the surface of the lunar soil simulant was uneven, mainly angular, long, and subangular, as shown in Figure 2. The main mineral composition of lunar soil simulant can be obtained by X-ray diffraction analysis, as shown in Figure 3. In order to ensure that it was close to the real lunar soil material, the crushed basalt was screened so that its particle size was similar to the real lunar soil particle size. The particle gradation curve of lunar soil simulant is shown in Figure 4 [38].

The sodium silicate used in the test came from anhydrous sodium silicate (Na₂SiO₃) produced by Tianjin Fuchen Chemical Reagent Factory. The modulus is 1.2, it is a white powdery solid, its PH value is 11, and it is easily soluble in water at room temperature.

The content of sodium silicate was the ratio of the mass of sodium silicate powder to the simulated lunar soil material, which were 0%, 3%, 5%, and 7%, respectively. After drying the lunar soil simulant and the sodium silicate powder, a certain amount of tap water was added to control the moisture content of 7.5% [literature [39, 40] confirmed that the moisture content of the lunar polar regions is between 5.6% and 11.5%), and then stirred evenly and stood for 12h.
2.2. Testing Method. The test was carried out on a quadruple strain-controlled direct shear instrument in the Geotechnical Laboratory of Anhui University of Science and Technology. The dial indicator in the stress ring has a range of 10 mm and a minimum scale of 0.1 mm. The diameter of the ring cutter used in the test is 61.8 mm and the height is 20 mm. The samples were compacted in layers with an automatic compactor, and each layer was needed to be shaved. The finished samples were wrapped with plastic wrap to prevent moisture loss. After curing for 14 days in a thermostat at 85°C, the samples were placed in a shear box for the direct shear test. The shear speed was 0.8 mm/min. The detailed test process is shown in Figure 5. Read the shear force when the sample was broken, calculate the shear strength from formula (1), and see Figure 6 for sample failure, so as to obtain the relationship between the shear strength, vertical pressure, and relevant shear parameters.

\[
\tau = \frac{CR}{A_0} \times 10, 
\]

where \(\tau\) is the failure shear stress of the sample (kPa), \(C\) is the dynamometer calibration coefficient (N/0.01 mm), \(R\) is the dynamometer reading (0.01 mm), and \(A_0\) is the initial area of the sample (cm²).

### Table 1: Chemical composition of the real lunar soil and lunar soil simulant.

<table>
<thead>
<tr>
<th>Chemical composition (%)</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>MnO</th>
<th>MgO</th>
<th>FeO</th>
<th>CaO</th>
<th>K₂O</th>
<th>P₂O₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSC-1</td>
<td>49.1</td>
<td>1.48</td>
<td>15.5</td>
<td>0.18</td>
<td>8.48</td>
<td>9.81</td>
<td>10.1</td>
<td>0.85</td>
<td>0.61</td>
</tr>
<tr>
<td>JSC-1A</td>
<td>46.2</td>
<td>1.85</td>
<td>17.1</td>
<td>0.19</td>
<td>6.87</td>
<td>11.2</td>
<td>9.43</td>
<td>0.85</td>
<td>0.62</td>
</tr>
<tr>
<td>CAS-1</td>
<td>49.24</td>
<td>1.91</td>
<td>15.8</td>
<td>0.14</td>
<td>8.74</td>
<td>11.47</td>
<td>7.25</td>
<td>1.02</td>
<td>0.3</td>
</tr>
<tr>
<td>Apollo14</td>
<td>48.10</td>
<td>1.70</td>
<td>17.40</td>
<td>0.14</td>
<td>9.40</td>
<td>10.40</td>
<td>10.70</td>
<td>0.55</td>
<td>0.51</td>
</tr>
<tr>
<td>Apollo15</td>
<td>46.95</td>
<td>1.6</td>
<td>12.7</td>
<td>0.21</td>
<td>10.75</td>
<td>16.29</td>
<td>10.49</td>
<td>0.092</td>
<td>0.16</td>
</tr>
<tr>
<td>Nanjing basalt</td>
<td>48.05</td>
<td>1.18</td>
<td>17.08</td>
<td>0.14</td>
<td>5.58</td>
<td>8.60</td>
<td>8.45</td>
<td>1.20</td>
<td>0.61</td>
</tr>
</tbody>
</table>

### Figure 2: The microscopic morphology of lunar soil simulant.

### Figure 3: The XRD pattern of lunar soil simulant.

### Figure 4: The particle gradation curve for lunar soil simulant.

### Figure 5: Testing procedures.
2.3. Direct Shear Test Results and Discussion

2.3.1. Shear Stress-Shear Displacement Curve Characteristics [43]. Figure 7 shows shear stress-displacement curves of the lunar soil simulant with different sodium silicate content. It can be seen from Figures 7(a) and 7(b) that under a given vertical pressure, the lunar soil simulant with sodium silicate content of 0% and 3% showed no obvious peak strength in the shear process, and its shear stress increased with the increase of shear displacement in the early stage, and then tended to be stable, showing strain hardening characteristics.

According to Figures 7(c) and 7(d), when the sodium silicate content was 5% and 7%, the initial shear stress of the solidified lunar soil simulant increased rapidly, namely, the shear modulus of solidified lunar soil simulant increased significantly. Compared with the lunar soil simulant sample without sodium silicate, the stress peak value was more obvious, but the shear stress would gradually decrease after reaching the peak value, and the shear stress-shear displacement curve presented the characteristics of strain softening. The reason for the above phenomenon can be explained as follows: under the action of peak shear stress, the cementation between the particles of the lunar soil simulant gradually disappeared, and the shear stress significantly decreased. In this process, the friction force on the failure surface of the sample was sliding friction. As the shear displacement increased, the shear stress gradually stabilized.

2.4. Shear Strength Characteristics [44]. According to the Mohr–Coulomb law,

\[
\tau_f = c + \sigma \tan \varphi,
\]

(2)

where \(\tau_f\) is the shear stress on the shear failure surface of the sample (kPa), \(c\) is the cohesive force of the lunar soil simulant (kPa), \(\sigma\) is the shear stress of the lunar soil simulant (kPa), and \(\varphi\) is the internal friction angle of the lunar soil simulant. [43].

In order to facilitate the analysis of the relationship between sodium silicate content, cohesion, and internal friction angle, the bar chart of the relationship between sodium silicate content, internal friction angle, and cohesion of the lunar soil simulant was drawn as shown in Figure 8 [45]. Figure 8 shows that (1) the cohesive force of the lunar soil simulant changed significantly with the amount of sodium silicate, while the sodium silicate content had no obvious effect on the internal friction angle. With the increase of sodium silicate content, the variation range of internal friction angle of the lunar soil simulant was small. (2) As the content of sodium silicate increased, the cohesion of the lunar soil simulant first increased and then decreased. It could be seen that the shear strength of sodium silicate was increased mainly by affecting the cohesion of the lunar soil simulant’s particles but had little effect on the angle of internal friction angle.

Figure 9 shows the envelope of shear strength of the lunar soil simulant with different sodium silicate content. It can be seen from Figure 9 that (1) the incorporation of sodium silicate could effectively improve the shear strength of the lunar soil simulant. With the increase of the sodium silicate content, the shear strength first increased and then decreased. When the sodium silicate content is 5%, the shear strength reached the maximum. (2) As the vertical pressure increased, the shear stress of the solidified lunar soil simulant also increased approximately linearly [46].

2.5. Shear Deformation Modulus and Peak Deformation. Shear modulus is a parameter that reflects the relationship between the shear load and deformation of the lunar soil simulant. The initial shear deformation modulus \(G_0\) is defined as the secant modulus corresponding to 0.4\(V_p\), and the peak shear deformation modulus \(G_m\) is the peak point [47]. Figure 10 shows the comparison of peak deformation and shear modulus of the lunar soil simulant in the direct shear test with different contents of sodium silicate.

It can be seen from Figure 10 that

(1) With the increase of sodium silicate content, the peak deformation of the lunar soil simulant increased, indicating that the addition of sodium silicate could improve the deformation performance of the lunar soil simulant, but the effect was not obvious.

(2) Shear modulus \(G_0\) and \(G_m\) showed a trend of first increasing and then decreasing with the increase of
sodium silicate content. When the sodium silicate content was 5%, the $G_0$ and $G_m$ of the lunar soil simulant reached the maximum, indicating that the hydration reaction in the system was severe at this time. As the strength of the lunar soil simulant increased, many small cracks appeared and extended rapidly in the lunar soil simulant under shear load, and the shear modulus also increased rapidly.

(3) When the sodium silicate content exceeded 5%, both the shear strength $G_0$ and $G_m$ showed a downward trend, indicating that excessive sodium silicate addition would lead to sodium silicate deposition, which could not fully react with the lunar soil simulant, thus reducing the strength and shear modulus.

2.6. Analysis of Energy Dissipation during Direct Shear. Figure 11 shows the curve of the whole process of the lunar soil simulant specimen under direct shear, which mainly went through three stages:
(1) Initial compaction stage: at the beginning of loading, the slope of the curve was small, and at this time, it was mainly the gap closure stage.

(2) Direct shear stage: with the increase of shear displacement, the slope of the curve had become larger, when the peak stress was near, the curve became flat until the peak stress was reached.

(3) Direct shear failure stage: after the shear stress reached the peak, the specimen was completely destroyed, but there was still a certain bearing capacity, namely, residual stress.

The curve ODEC was the actual loading path of the specimen under shear load, and the energy generated was $Q = Q_e + Q_p$, where $Q_e$ was elastic deformation energy and $Q_p$ was plastic deformation energy. In the figure, OABC was the stress state of the specimen in the ideal state, and the work was recorded as $Q$. In order to better analyze the energy dissipation of lunar soil simulant during direct shear, the energy dissipation coefficient was introduced [48, 49]

$$\beta = \frac{Q_1}{Q} = \frac{S_{ODEC}}{S_{OABC}}$$  (3)

Figure 12 shows the comparison of energy dissipation of the lunar soil simulant with different sodium silicate content, and it can be seen from Figure 12 that the energy dissipation coefficient of the lunar soil simulant in the shear process was in the range of 0.75–0.81. With the increase of sodium silicate content, the energy dissipation coefficient of the lunar soil simulant increased slightly, indicating that the addition of sodium silicate could improve the energy dissipation capacity of the lunar soil simulant to a certain extent [50, 51].
3. Mechanism Analysis of Strength Variation of the Lunar Soil Simulant by Sodium Silicate Solidification

3.1. X-Ray Diffraction Analysis. X-ray diffraction is an important method to analyze the composition of crystal minerals. X-ray diffraction analysis was performed on lunar soil simulant samples with different amounts of sodium silicate to analyze the substances generated in the system after adding sodium silicate.

Figure 13 shows the X-ray diffraction spectrum of the lunar soil simulant with sodium silicate content of 3%, 5%, and 7%. According to the distribution of the diffraction peaks of each component, it can be clearly observed that the main mineral components of the lunar soil simulant are mainly anorthite, albite, and pyroxene. After adding sodium silicate, the diffraction intensity of some minerals changed, the diffraction intensity of anorthite increased, and dense amorphous materials increased. There was obvious formation of silicate polymer gel (N-A-S-H) in the region of $2\theta < 60^\circ$. Wang et al. [52] found that the alkali activator could effectively stimulate the active components of silica-alumina geopolymer, cause the fracture of Si-O bond and Al-O bond in the vitreous structure, and repolymerize to form N-A-S-H gel. At the same time, with the increase of sodium silicate content, the Aft diffraction peak was found in the system. Jian et al. [53] showed that the early hydration products of silica-alumina geopolymers were mainly trisulfide hydrated calcium sulfoaluminate (Aft) and hydrated calcium silicate gel.

3.2. SEM Microscopic Analysis. Figure 14 shows the SEM microscopic test results of the lunar soil simulant with different sodium silicate content. Figure 14(a) shows the lunar soil simulant’s particles magnified by 10000 times. It was obvious that the lunar soil simulant’s particles were irregularly arranged with prominent edges and angles, the pores between the particles were relatively large, which could provide a feasible environment for the subsequent sodium silicate reaction process, enabling the hydration reaction and cementation to be carried out smoothly.

3.3. Analysis of Strength Variation Mechanism of Lunar Soil Simulated by Sodium Silicate Solidification

3.3.1. Alkali Excitation Effect of Sodium Silicate on the Lunar Soil Simulant. The main components of the lunar soil simulant are SiO$_2$ and Al$_2$O$_3$, and NaOH and silicic acid are generated after hydrolyzation of sodium silicate. As shown...
in Figure 15(a), OH$^-\$ promotes the rupture of Si-O and Al-O bonds in the simulated lunar vitreous; silicic acid provides a large amount of active silicon so that silicon ions and aluminum ions in the system react with basic silicoaluminate and hydrate to generate N-A-S-H gel, AFt, etc. The N-A-S-H gel film not only strengthens the bonding force of cement between the lunar soil simulant’s skeleton particles but also limits the deformation of the lunar soil simulant’s particles themselves, and it also has strength, resulting in an increase in the shear strength of the lunar soil simulant.

### 3.3.2. Adsorption between Sodium Silicate and Minerals in Lunar Soil Simulant’s Particles

As shown in Figure 15(b), the dissolution of silicon and aluminum in the lunar soil simulant’s particles reacts with the sodium silicate, while silicate ions and silica gel are adsorbed on the surface of the lunar soil simulant’s particles to form large colloidal particles. Due to the unstable structure of silicon-oxygen and silicon-aluminum tetrahedrons, polycondensation reaction occurs easily, forming a silicate gel coexisting network structure product with a high degree of polymerization, which is deposited between the pores of the particles, and a large amount of gel is wrapped by adsorption on the surface of the framework particles. When the amount of sodium silicate is too much, in addition to increasing the excitation speed, a large amount of gel is generated, which wraps the unreacted part and prevents the reaction from proceeding.

### 4. Conclusions

(1) The shear stress-displacement curve of the sodium silicate curing lunar soil simulant mainly experienced three stages: compaction stage, local shear stage, and shear failure stage. Compared with the lunar soil simulant without sodium silicate, the peak stress is obvious, and the shear stress-shear displacement curve shows strain softening characteristics.
(2) The effect of sodium silicate content on the shear strength of lunar soil simulant is remarkable. With the increase of sodium silicate content, the shear strength of lunar soil simulant increases first and then decreases. When the vertical pressure is 400 kPa and the sodium silicate content is 5%, the shear strength is 559.81 kPa, and the envelope lines of the samples are almost parallel to each other. When the sodium silicate content was 0%, the cohesion of the simulated lunar soil was 8.35 kPa and the internal friction angle was 39.52°. When the sodium silicate content was 5%, the cohesion of the simulated lunar soil was 49.48 kPa and the internal friction angle was 52.88°. It can be seen that sodium silicate increases its shear strength mainly by changing the cohesion of lunar soil simulant and has little effect on its internal friction angle.

(3) With the increase of sodium silicate content, the shear deformation modulus of lunar soil simulant increases first and then decreases. When the sodium silicate content is 5%, the initial shear deformation modulus and the peak shear deformation modulus of the lunar soil simulant reach the maximum. The incorporation of sodium silicate improved the peak deformation and energy dissipation capacity of lunar soil simulant.

(4) The microscopic test shows that the internal microstructure of lunar soil simulant changes under the excitation of sodium silicate. Alkali excitation of sodium silicate and adsorption of sodium silicate with feldspar and minerals in lunar soil simulant’s particles result in the formation of N-A-S-H gel, AFt, and other products, which makes the originally loose lunar soil simulant particles adhere to a close spatial network structure through gel macroscopically corresponding to the increase in shear strength of the lunar soil simulant.

In the future, we will study the properties of the simulated lunar soil solidified by sodium silicate at extremely low temperature so as to study the mechanical properties of the polymer in the simulated lunar soil more comprehensively.

Data Availability

The data of this study are available from the author if required.

Conflicts of Interest

All authors declare that they have no conflicts of interest.

Acknowledgments

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