Planetary and Space Science 226 (2023) 105630

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Shear properties of LHS-1 and LMS-1 Lunar regolith simulants

Kexin Yin [a,*], Zhichao Cheng [b], Jiangxin Liu [c], An Chen [d]

[a] *Department of Civil and Airport Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, 211106, China*
[b] *PowerChina Huadong Engineering Corporation Limited, Hangzhou, 311122, China*
[c] *Research Institute of Highway Ministry of Transport, Beijing, 100088, China*
[d] *Faculty of Land Resources Engineering, Kunming University of Science and Technology, Kunming, 650093, China*

ARTICLE INFO

Handling Editor: Dr Witasse Witasse

Keywords:
Lunar regolith simulant
Lunar highlands simulant (LHS-1)
Lunar mare simulant (LMS-1)
Shear strength
Soil-structure interaction

ABSTRACT

Lunar exploration and in-situ resource utilization (ISRU) activities need a better understanding of the geotechnical properties of the Lunar regolith. However, due to the Lunar regolith specimens brought from the Moon are scarce on the Earth, a lot of Lunar regolith simulants have been produced by using terrestrial-based materials for experiments. This study reports the shear characterization of two new Lunar regolith simulants named LHS-1 and LMS-1. Direct shear tests were carried out on the two simulants to characterize their shear properties, the results show that the cohesion and internal friction angles of LHS-1 and LMS-1 are similar to actual Lunar regolith and other existing simulants. Additionally, a series of direct shear tests were performed on the interface between LHS-1/LMS-1 and steel plates. Surface roughness was varied to investigate the interfacial shear behavior of the two Lunar simulants at both peak and residual conditions.

1. Introduction

Lunar exploration and in-situ resource utilization (ISRU) activities demand well-constrained information about the geotechnical properties of Lunar regolith. Shear properties especially the cohesion and friction angle of lunar regolith are useful for exploration mission preparation, hardware design, and infrastructure construction on the Moon (Frost and Martinez, 2018; Iai and Luna, 2011; Long-Fox et al., 2021b, 2022; Marzulli and Cafaro, 2019; Yin et al., 2021b). Lunar simulants with similar chemical compositions as well as physical properties to Lunar regolith are created with terrestrial materials for scientific testing on the Earth, due to a large quantity of returned Lunar regolith being unavailable for geotechnical experiments (Ryu et al., 2018; Zeng et al., 2010). Two specific geological regions exist on the Moon, i.e., the Lunar highlands and Lunar mare, which are characterized by different mineralogical compositions and geotechnical properties. For instance, the Lunar south pole is a highlands region mainly composed of anorthosite, while the Lunar mare is rich in basalt (Lemelin et al., 2022; Long-Fox et al., 2021a, 2022). To represent the Lunar highlands and mare regolith and to satisfy the needs of large quantities of Lunar regolith-like soils for Lunar research, two high-fidelity simulants are developed and produced by the CLASS Exolith Lab at the University of Central Florida, namely the Lunar highlands simulant (LHS-1) and Lunar mare simulant (LMS-1). Since LHS-1 and LMS-1 can accurately simulate the Lunar highlands and mare regolith from the aspects of mineralogical composition, mechanical features, particle size and shape distributions (Cannon and Britt, 2019; Isachenkov et al., 2022; Long-Fox et al., 2022), they become appropriate analogies for the geotechnical characterization of the regolith in the two different Lunar regions. However, several important geotechnical properties of the two new Lunar regolith simulants are not well investigated and understood, for example, the cohesion and friction angle. Moreover, the shear response has often been monitored on the simulants themselves (Iai and Luna, 2011; Long-Fox et al., 2022; Marzulli and Cafaro, 2019; Ryu et al., 2018; Seehanam et al., 2021; Suescun-Florez et al., 2015), with no consideration on the simulant-structure interfaces.

This study mainly investigates the shear properties of the LHS-1 and LMS-1 simulants-steel interfaces regarding smooth and rough surface conditions, thanks to a novel interface direct shear machine accompanied with an accurate monitoring system. The differences in interface shear strength parameters between regolith simulants LHS-1 and LMS-1 are quantified and compared. This research aims to establish some baseline geotechnical data for the two Lunar simulants as well.

---

* Corresponding author.
E-mail address: kexin.yin@nuaa.edu.cn (K. Yin).

https://doi.org/10.1016/j.pss.2022.105630
Received 8 November 2022; Received in revised form 11 December 2022; Accepted 27 December 2022

2. Materials and methods

2.1. Materials

Two novel Lunar simulants designed by the CLASS Exolith Lab were used in the direct shear tests, i.e., the Lunar highlands simulant (LHS-1) and Lunar mare simulant (LMS-1). The grain size distribution curves are shown in Fig. 1a, presenting the data measured by both laser diffraction and sieve analysis in Exolith Lab. All the particle size of the two simulants is lower than 100 μm, and their mean particle diameter is about 60 μm. The particles of the two Lunar simulants are characterized with angular shape, providing enough similarity for actual Lunar regolith. Glass spherules and agglutinates are absent in the morphology of the particles (Isachenkov et al., 2022), which are typical space-weathering features of Lunar regolith developed under conditions of proton sputtering, micrometeorite impact, and solar wind etching. The grain density (ρ_s) of LHS-1 and LMS-1 is 3.22 g/cm^3 and 3.03 g/cm^3, and their bulk density (ρ_a) is 1.30 g/cm^3 and 1.56 g/cm^3, respectively (measured by Exolith Lab). The minimum ($\rho_{\min}$) and maximum ($\rho_{\max}$) density of LHS-1 measured in our lab are 1.39 g/cm^3 and 1.91 g/cm^3, quite close to 1.24 g/cm^3 and 1.95 g/cm^3 tested by Exolith Lab. The minimum and maximum density of LMS-1 are 1.56 g/cm^3 and 2.06 g/cm^3. The different particle size distribution by mass (Fig. 1a) and mineral component cause different minimum and maximum density for the two simulants. The chemical and mineral composition of LHS-1 and LMS-1 measured by X-ray fluorescence (XRF) and X-ray diffraction (XRD) techniques agree with data acquired from corresponding genuine Lunar highlands and mare regolith, according to the comparison in Isachenkov et al. (2022). The mineral composition of the two Lunar regolith simulants is summarized in Table 1. More information about the particles' morphology and chemical components of LHS-1 and LMS-1 can be found in Fact sheets from the Exolith Lab and Isachenkov et al. (2022).

Steel plates in a dimension of 140 mm × 100 mm × 11 mm with different roughness (i.e., smooth and rough) were employed for the simulant-structure interface direct shear tests. The investigated smooth and rough surfaces aimed to simulate different interface roughness encountered in engineering problems of ISRU (e.g., rover mobility, wheel-regolith interaction, infrastructure construction, mineral exploration, regolith transportation, and excavation tools). The shear response of the Lunar soil-structure interface is affected by the interface roughness and asperities of the regolith particles (Brisset et al., 2022; Frost and Martinez, 2018; Prabu et al., 2021; Sun et al., 2022; Yin et al., 2021a). Two kinds of roughness parameters of the two steel plates are measured, i.e., the average arithmetic height (R_a) and the maximum peak-to-valley height ($R_{\max}$). The R_a values are 1 μm and 45 μm, and the $R_{\max}$ values are 8 μm and 277 μm, to define the smooth and rough plates. The steel plate was installed in the bottom part of the interface shear box, see Fig. 1b.

Table 1
Mineral composition of the two Lunar regolith simulants.

Component (wt.%)	LHS-1	LMS-1
Anorthosite	74.4	19.8
Glass + basalt	24.7	32.0
Ilmenite	0.4	4.3
Pyroxene	0.3	32.8
Olivine	0.2	11.1

Lunar simulant specimen was poured into the shear box, and then a manual compaction was performed by a tamping tool to obtain a sample density of 1.85 g/cm^3 and 1.97 g/cm^3 for LHS-1 and LMS-1, respectively. The values of the relative density (D_r) of LHS-1 and LMS-1 are 86.0% and 85.0%, indicating dense Lunar simulant samples. Then the whole shear box was installed in the interface direct shear machine for the shearing test.

2.2. Direct shear device

An interface direct shear machine (see Yin (2021)) was used to investigate the shear behavior of the LHS-1 and LMS-1 Lunar simulants. The upper part of the shear box is 100 mm × 100 mm × 50 mm for accommodating a Lunar simulant specimen, while the dimension of the groove in the bottom part is 140 mm × 100 mm × 11 mm for containing a steel plate (Fig. 1b). The vertical/horizontal loads applied to the specimen are measured by accurate load cells. Horizontal/vertical displacements are recorded by two Linear Voltage Displacement Transformers (LVDTs). The data logging system of the direct shear machine offers a minimum acquisition rate of 0.001 s. More details about the interface machine can be referred to Vasilescu (2019) and Yin (2021).

2.3. Experimental setup

Direct shear tests with the displacement-controlled mode were performed on dry LHS-1 and LMS-1 simulants as a first part of the present experiment setup to estimate the cohesion and angle of internal friction. The normal stresses employed were 25 kPa, 50 kPa and 75 kPa. A series of displacement-controlled interface direct shear tests were conducted on dry Lunar simulants-steel under four constant normal stresses of 25 kPa, 50 kPa, 75 kPa, and 100 kPa to characterize the shear properties at both smooth and rough steel surface conditions. When the vertical deformation was stable after the normal stress was applied, all the direct and interface direct shearing tests were performed with a rate of 0.5 mm/min, reaching a maximum horizontal displacement of 10 mm.

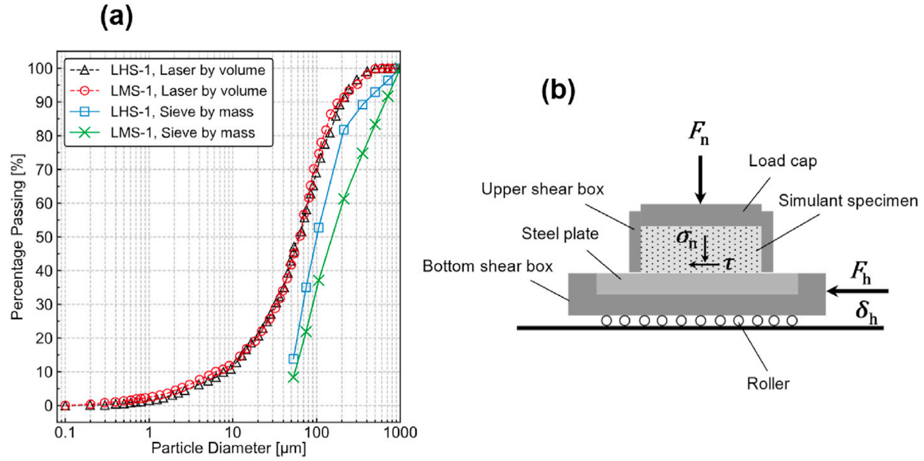

Fig. 1. (a) Particle size distribution curves of LHS-1 and LMS-1 Lunar simulants; (b) sketch of the interface direct shear box.

3. Experimental data

The shear stress versus horizontal displacement of the direct shear tests is compared in Fig. 2a. LHS-1 is mobilized with larger peak shear stress (τ_p) at the normal stress of 50 kPa and 75 kPa than LMS-1. Whereas similar residual shear stresses (τ_{cv}) are observed for the two Lunar simulants under the three normal stresses studied. Direct shear data is processed by linear regression according to the Mohr-Coulomb relationship between shear stress and normal stress to obtain the cohesion and internal friction angle. The peak/residual cohesion (c_p, c_{cv}) values are 0/1.7 kPa and 5.3/3.9 kPa for LHS-1 and LMS-1, respectively (Fig. 2b). The estimated peak/residual angles of internal friction (φ_p, φ_{cv}) are 45.1°/40.3° and 40.9°/40.5° for LHS-1 and LMS-1, respectively. There are obvious differences on the peak internal friction angles between LHS-1 and LMS-1, this can be attributed to the different initial sample density and mineralogical composition (Table 1). Since the two simulants have a same particle size distribution by volume (see Fig. 1a), they exhibit nearly the same residual friction angles. In other words, the granulometry controls the residual friction angle, with respect to other compositional factors, such as mineralogy.

The residual cohesion and internal friction angles are compared to the data from Lunar regolith and other Lunar simulants in the literature, as presented in Table 2. The cohesion (c) and internal friction angle (φ) of genuine lunar regolith are in the range of 0.26–2.1 kPa and 25–50° (Carrier et al., 1973; Mitchell et al., 1972), the c_{cv} and φ_{cv} of LHS-1 and LMS-1 are successfully fitting within this range. The cohesion values of LHS-1 and LMS-1 obtained in this study are in accordance with other simulants like BP-1 (Suescun-Florez et al., 2015), JSC-1A (Alshibli and Hasan, 2009), KLS-1 (Ryu et al., 2018), JSC-1 (Ryu et al., 2018), higher than LHS-1 (Long-Fox et al., 2022) and DNA-1A (Marzulli and Cafaro, 2019), but lower than the results of LMS-1 (Long-Fox et al., 2021b), TLS-01 (Seehanam et al., 2021) and FJS-1 (Ryu et al., 2018). The residual internal friction angles of LHS-1 and LMS-1 have similar values with reported results of the simulants in Table 2, except for the LHS-1, LMS-1 tested by Exolith Lab and TLS-01 tested by Seehanam et al. (2021). This is mainly due to the tested sample density of dried LHS-1 and LMS-1 in Long-Fox et al. (2022) and Long-Fox et al. (2021b) is lower, and the TLS-01 from Seehanam et al. (2021) was produced with grinding machine rather than conventional jaw crusher or hammer mill.

Table 2
Residual cohesion and internal friction angles of LHS-1 and LMS-1 compared to values for Lunar regolith and other Lunar simulants.

	Cohesion (kPa)	Internal friction angle (°)
LHS-1	1.7	40.3
LMS-1	3.9	40.5
BP-1[a]	0.0–2.0	39–51
JSC-1A[b]	2.0–5.0	37–48
KLS-1[c]	1.85	44.9
JSC-1[c]	1.65	45.0
JSC-1[d]	≤1.0	45.0
FJS-1[e]	3–8.4	32.5–39.4
LHS-1[f]	0.301 ± 0.013	31.7 ± 2.4
LMS-1[g]	0.341 ± 0.022	49.6 ± 3.9
DNA-1A[h]	0.0	44–47
TLS-01[i]	6.5	33.9
FJS-1[c]	8.13	39.4
Lunar regolith[j]	0.26-1.80	25–50
Lunar regolith[k]	0.3-2.1	35–47

[a] Suescun-Florez et al. (2015).
[b] Alshibli and Hasan (2009).
[c] Ryu et al. (2018).
[d] Willman et al. (1995).
[e] Kanamori et al. (1998).
[f] Dried LHS-1 data from Long-Fox et al. (2022).
[g] Long-Fox et al. (2021b).
[h] Marzulli and Cafaro (2019).
[i] Seehanam et al. (2021).
[j] Carrier et al. (1973)
[k] Apollo 11, Apollo 12, and Apollo 14 data from Mitchell et al. (1972).

So far, there is no data about the interface shear response between LHS-1/LMS-1 Lunar simulants and structures typically characterized by direct shear test. The changes in shear stress with respect to horizontal displacement of the two simulants-steel plate under smooth surface conditions are presented in Fig. 3. Prominent curve peaks appear at higher normal stress (i.e., 75 kPa and 100 kPa), which agrees with the findings presented by Frost and Martinez (2018) for two Lunar simulants (JSC-1A and GRC-3). Comparable trends are exhibited in both curves, however LMS-1 needs less horizontal displacement to reach peak shear stress (τ_p) than LHS-1. The mineral composition, particle size and shape, as well as the sample density are attributed to this difference (Long-Fox et al., 2021b). Similar peak (τ_p) and residual (τ_{cv}) shear stress values are observed on LHS-1 and LMS-1 (Fig. 3), giving quite close peak and residual interface friction angles with a small difference of 0.7°–1.0°. The peak adhesion (c_p) obtained from the intercept of Mohr-Coulomb envelopes on shear stress axis is 2.8 kPa and 2.3 kPa for LHS-1 and LMS-1, respectively. The residual adhesion (c_{cv}) values of them are 2.4 kPa and 2.2 kPa (Fig. 3b).

Data from all tests of rough interface shearing are presented in terms of shear stress-horizontal displacement and Mohr-Coulomb failure envelopes (Fig. 4). There are distinct peaks on all the shear stress-horizontal displacement curves of both LHS-1 and LMS-1 in the case of rough steel surface. Peak shear stresses are generated at a horizontal displacement smaller than 2 mm (Fig. 4a). Although there exist differences (1.42–4.25 kPa) on the peak shear strength for LHS-1 and LMS-1, similar residual shear strength is mobilized with a small magnitude of 0.37–2.33 kPa

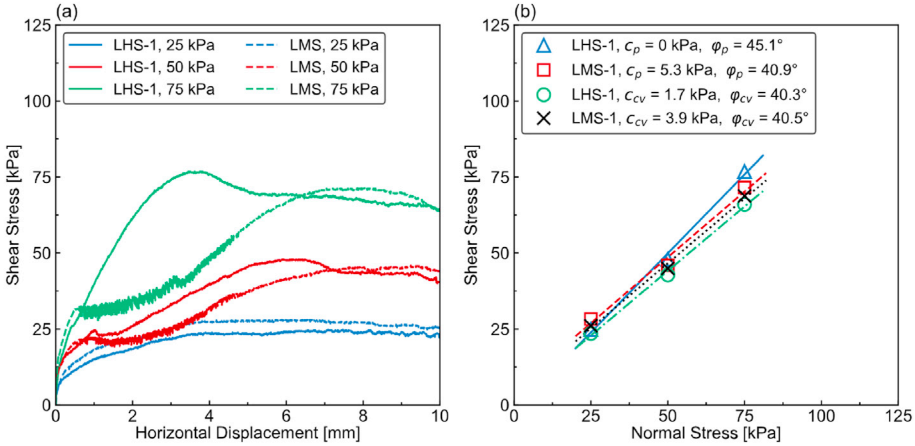

Fig. 2. Direct shear test results of LHS-1 and LMS-1: (a) shear stress as a function of horizontal displacement, and (b) peak and residual failure envelopes.

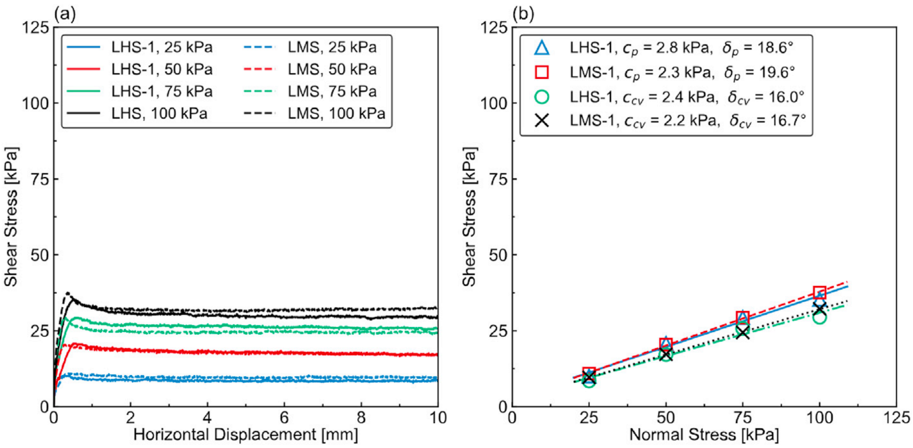

Fig. 3. Smooth interface direct shear test results of LHS-1 and LMS-1: (a) shear stress as a function of horizontal displacement, and (b) peak and residual failure envelopes.

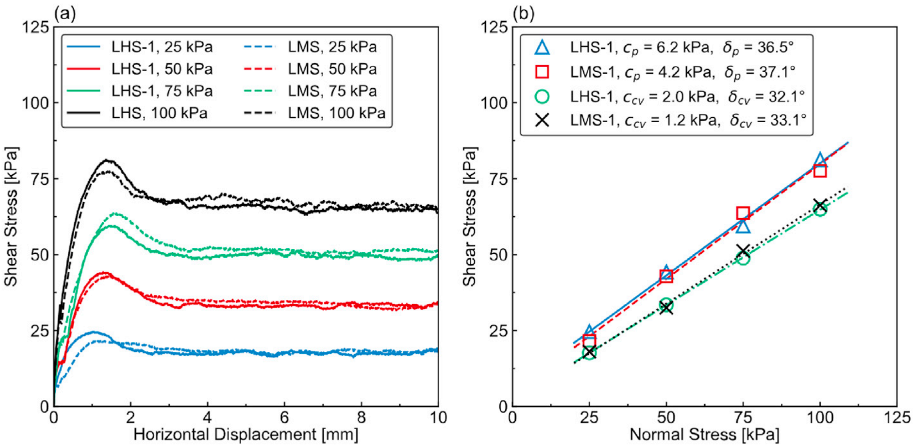

Fig. 4. Rough interface direct shear test results of LHS-1 and LMS-1: (a) shear stress as a function of horizontal displacement, and (b) peak and residual failure envelopes.

(Fig. 4). Like the smooth interface shear tests, the shear stress curves get to a constant volume state at a horizontal displacement of 6 mm–10 mm. Since surface roughness is an influence factor on the shear behavior (Frost and Martinez, 2018; Yin et al., 2021a), higher residual shear strength is observed on rough interface than the smooth one (see Figs. 3 and 4).

The peak adhesion (c_p) values under the rough interface condition are 6.2 kPa and 4.2 kPa for LHS-1 and LMS-1, as shown in Fig. 4b. While the residual adhesion (c_{cv}) is much lower than the peak one, 2.0 kPa for LHS-1 and 1.2 kPa for LMS-1. In general, the cohesion of the soil-structure interface is lower than the cohesion of soils (Yin et al., 2021a), however in this study the interface adhesion values of both smooth and rough plates are quite close to the cohesion values of the simulants (see Figs. 2, Figs. 3 and 4), this may be due to the Lunar simulants are low cohesive materials and the direct shear test is not an optimal method to determine the cohesion or adhesion of granular materials. When the steel plate surface is rough, LHS-1 is characterized with a little bit lower peak and residual interface friction angles than LMS-1 (Fig. 4), a similar trend is also observed in the smooth plate surface tests in Fig. 3. As presented in Fig. 4b, the δ_p of LHS-1 is 36.5°, only 0.6° lower than LMS-1; the δ_{cv} of LHS-1 is 32.1° while the one of LMS-1 is 33.1°. The difference of initial specimen density, particle size distribution (by mass), mineral composition and particle geometry are the main reasons for that LHS-1 has lower interface friction angles than LMS-1.

The peak and residual interface friction angles of LHS-1 and LMS-1 increase with interface roughness, but still lower than the internal friction angles of the simulants at the studied interface roughness range (R_a < 50 μm and R_{max} < 300 μm). This finding agrees with the previously published results of interface shear tests on other Lunar simulants, e.g., JSC-1A and GRC-3 in Frost and Martinez (2018).

4. Conclusions

Direct shear tests were conducted on LHS-1 and LMS-1 Lunar simulants, as well as the simulant-steel interface, to investigate the corresponding shear properties under different surface roughness. The two new Lunar simulants are suitable for Earth-based experiments to study the geotechnical properties of the regolith on Lunar highlands and Lunar mare. The conclusions are summarized as follows.

1. Direct shear: the peak/residual cohesion (c_p, c_{cv}) values are 0/1.7 kPa and 5.3/3.9 kPa for LHS-1 and LMS-1, respectively. The peak/residual internal friction angles (φ_p, φ_{cv}) are 45.1°/40.3° and 40.9°/40.5° for LHS-1 and LMS-1. The c_{cv} and φ_{cv} of LHS-1 and LMS-1 measured in this study are consistent with genuine Lunar regolith and other major Lunar simulants in the literature.
2. Smooth interface: the peak and residual adhesion values of LHS-1 and LMS-1 are <3.0 kPa; the difference of peak interface friction angles of

LHS-1 (18.6°) and LMS-1 (19.6°) is 1.0°, and the residual interface friction angle difference of LHS-1 (16.0°) and LMS-1 (16.7°) is only 0.7°.

3. Rough interface: the peak and residual adhesion values of LHS-1 and LMS-1 are <6.5 kPa; the peak interface friction angles of them are 36.5° and 37.1°, and the residual values are 32.1° and 33.1°, for LHS-1 and LMS-1, respectively.
4. The interface friction angles of LHS-1 are lower than LMS-1, mainly due to their different initial specimen density, particle size distribution, mineral composition and particle geometry.
5. The peak and residual interface friction angles of LHS-1 and LMS-1 increase with surface roughness, but still smaller than the internal friction angles of the two simulants at the studied roughness range of $R_a < 50$ μm and $R_{max} < 300$ μm.
6. The mechanical parameters of the two Lunar simulants-steel interface can provide information for future human construction on the Moon.

However, more geotechnical properties of the two Lunar simulants require further and intensive investigation across various conditions.

Credit author statement

Kexin Yin: Conceptualization, Methodology, Funding acquisition, Investigation, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. Zhichao Cheng: Conceptualization, Methodology, Writing - review & editing. Jiangxin Liu: Visualization, Formal analysis, Writing - review & editing. An Chen: Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge the program “Fundamental Research Funds for the Central Universities (90YAT22006)” for funding the research reported here.

References

Alshibli, K.A., Hasan, A., 2009. Strength properties of JSC-1A lunar regolith simulant. J. Geotech. Geoenviron. Eng. 135, 673–679.

Brisset, J., Sánchez, P., Cox, C., Corraliza, D., Hatchitt, J., Madison, A., Miletich, T., 2022. Asteroid regolith strength: role of grain size and surface properties. Planet. Space Sci. 220, 105533.

Cannon, K., Britt, D., 2019. Mineralogically accurate simulants for lunar ISRU, and strategic regolith processing. In: Lunar ISRU 2019-Developing a New Space Economy Through Lunar Resources and Their Utilization, 2152, p. 5002.

Carrier III, W., Mitchell, J.K., Mahmood, A., 1973. The nature of lunar soil. J. Soil Mech. Found Div. 99, 813–832.

Frost, J.D., Martinez, A., 2018. Interface shear response of JSC-1A, GRC-3, and JSC-Mars1 regolith simulants. J. Aero. Eng. 31, 04018003.

Iai, M., Luna, R., 2011. Direct shear tests on JSC-1A lunar regolith simulant. J. Aero. Eng. 24, 433–441.

Isachenkov, M., Chugunov, S., Landsman, Z., Akhatov, I., Metke, A., Tikhonov, A., Shishkovsky, I., 2022. Characterization of novel lunar highland and mare simulants for ISRU research applications. Icarus 376, 114873.

Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto, S., Takagi, K., 1998. Properties of lunar soil simulant manufactured in Japan. Space 98, 462–468.

Lemelin, M., Lucey, P.G., Camon, A., 2022. Compositional maps of the lunar polar regions derived from the Kaguya spectral profiler and the lunar orbiter laser altimeter data. Planetary Sci. J. 3, 63.

Long-Fox, J., Lucas, M.P., Landsman, Z., Millwater, C., Britt, D., Neal, C., 2022. Applicability of Simulants in Developing Lunar Systems and Infrastructure: Geotechnical Measurements of Lunar Highlands Simulant LHS-1, vol. 2022. ASCE Earth and Space, Denver, Colorado.

Long-Fox, J.M., Landsman, Z., Britt, D., Gonzalez, J.M., 2021a. Statistical Comparison of Shear Strength for Lunar Regolith Simulants LHS-1 and LMS-1, NASA Exploration Science Forum and European Lunar Symposium 2021. Virtual Meeting.

Long-Fox, J.M., Landsman, Z., Britt, D., Gonzalez, J.M., Schultz, C., 2021b. Quantifying the Shear Strength Properties of Lunar Regolith Simulants LHS-1 and LMS-1, Luxembourg Space Resources Week 2021 (Luxembourg).

Marzulli, V., Cafaro, F., 2019. Geotechnical properties of uncompacted DNA-1A lunar simulant. J. Aero. Eng. 32, 04018153.

Mitchell, J.K., Bromwell, L.G., Carrier III, W.D., Costes, N.C., Scott, R.F., 1972. Soil mechanical properties at the Apollo 14 site. J. Geophys. Res. 77, 5641–5664.

Prabu, T., Muthukkumaran, K., Venugopal, I., Anbazhagan, S., 2021. Assessment of shear strength and compressibility characteristics of a newly developed lunar highland soil simulant (LSS-ISAC-1) for Chandrayaan lander and rover missions. Planet. Space Sci. 209, 105354.

Ryu, B.-H., Wang, C.-C., Chang, I., 2018. Development and geotechnical engineering properties of KLS-1 lunar simulant. J. Aero. Eng. 31, 04017083.

Seehanam, S., Santironnarong, S., Meesuay, W., Soralump, S., Thowiwat, W., Jitklongsub, S., Chancharoen, W., 2021. Development and Mechanical Properties of the First Thailand Lunar Regolith Simulant. TLS-01.

Suescun-Florez, E., Roslyakov, S., Iskander, M., Baamer, M., 2015. Geotechnical properties of BP-1 lunar regolith simulant. J. Aero. Eng. 28, 04014124.

Sun, X., Zhang, R., Li, X., Zou, M., Wang, C., Chen, L., 2022. JLU-H: a novel lunar highland regolith simulant for use in large-scale engineering experiments. Planet. Space Sci. 221, 105562.

Vasilescu, A.-R., 2019. Design and execution of energy piles: Validation by in-situ and laboratory experiments. École centrale de Nantes.

Willman, B.M., Boles, W.W., McKay, D.S., Allen, C.C., 1995. Properties of lunar soil simulant JSC-1. J. Aero. Eng. 8, 77–87.

Yin, K., 2021. Influence of Clay Fraction on the Mechanical Behavior of a Soil-Concrete Interface. École centrale de Nantes.

Yin, K., Fauchille, A.-L., Di Filippo, E., Kotronis, P., Sciarra, G., 2021a. A review of sand–clay mixture and soil–structure interface direct shear test. Geotechnics 1, 260–306.

Yin, K., Liu, J., Lin, J., Vasilescu, A.-R., Othmani, K., Di Filippo, E., 2021b. Interface direct shear tests on JEZ-1 Mars regolith simulant. Appl. Sci. 11, 7052.

Zeng, X., He, C., Oravec, H., Wilkinson, A., Agui, J., Asnani, V., 2010. Geotechnical properties of JSC-1A lunar soil simulant. J. Aero. Eng. 23, 111–116.