Density, strength and compressibility characteristics of lunar regolith simulant

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ABSTRACT: Humankind will soon be returning to the Moon, as part of NASA's Artemis program, where the objective is long-term habitation to facilitate extra-terrestrial exploration and in situ resource utilisation. The Artemis program is focused on inhabiting the Moon's South pole, which consists of lunar highlands regolith. The Lunar Construction Group, which is part of the University of Adelaide's Andy Thomas Centre for Space Resources (ATCSR), is actively undertaking research to design and construct infrastructure on the Moon. Due to the lack of availability of lunar regolith samples, lunar simulants have been developed which are intended to provide authentic surrogates of lunar regolith. It is essential, for the development of sustainable and resilient lunar infrastructure, that the geotechnical characteristics of the regolith are quantified and understood. This paper begins by first summarising the known ground conditions on the Moon and then presents the results of laboratory testing on three lunar simulants LHS-1 (lunar highland simulant), MAB-1 (a modified lunar highland simulant, which is a mixture of anorthosite and basalt), and LMS-1 (lunar mare simulant), in order to quantify their strength and compressibility characteristics.

KEYWORDS: Moon, Specific Gravity, Particle Size, Compaction, Shear Strength.

1 INTRODUCTION

NASA's Artemis program is an ambitious mission to land humans on the lunar surface, with the goal of establishing a permanent presence on the Moon, with a focus on the lunar South Pole region. The ultimate goal of this program is to use the Moon as a steppingstone for deeper space exploration, including interplanetary missions, such as journeys to Mars. To achieve these objectives, NASA plans to establish various infrastructure on the Moon such as roads, buildings, and spaceport foundations.

1.1 *Understanding the Moon and its surface*

In order to construct infrastructure on the lunar surface, it is important to understand the basic characteristics of the Moon and its ground surface. Table 1 highlights the key differences between the Earth and the Moon, including variations in gravity, temperature, and radiation levels. These characteristics provide unique opportunities for utilising the lunar environment and its resources for future space exploration. Understanding these differences is crucial for the successful development of human-made structures on the lunar surface.

Table 1. Physical properties of the Moon and Earth (Vaniman et al. 1991b).

Property	Moon	Earth
Mass (kg)	7.353×10^{22}	5.976×10^{24}
Mean Density (g/cm^3)	3.34	5.517
Gravity at equator (m/s^2)	1.62	9.81
Escape velocity at equator	2.38 km/sec	11.2 km/sec
Mean surface temperature	107°C day, –153°C night	22°C
Temperature extremes	–233 to 123°C	–89 to 58°C
Atmosphere (molecules/cm^3)	~ 10^4 day; 2×10^5 night	2.5×10^{19}

The material that covers the lunar surface, which is referred to as lunar regolith, is composed of a complex mixture of five fundamental particle types: crystalline rock fragments, mineral fragments, breccias, agglutinates, and glasses (Carrier III et al. 1991). The lunar surface can be broadly classified into lowland and highland regions. The lowland regions are dark, basaltic plains created by the solidification of lava, which developed during previous eras of lunar volcanism, and these regions are referred to as lunar maria. These areas occupy around 17% of the Moon's surface. In contrast, the highland areas consist of anorthosite bedrock and are heavily cratered. The soils of the highlands regions are relatively rich in aluminium and calcium, while the soils of the maria are rich in iron, magnesium, and titanium (Vaniman et al. 1991a).

For the successful execution of lunar missions, it is essential to understand the geotechnical characteristics of lunar regolith. This understanding is crucial for the design and development of rovers, landing craft, and lunar landers (Thannasi et al. 2021), as well as the design and performance of infrastructure. Additionally, the geotechnical characteristics of lunar regolith are critical for in situ resource utilisation (ISRU) related activities that will provide the raw materials for sustained lunar habitation and exploration. Between 1969 and 1972, the Apollo missions returned almost 400 kg of Moon regolith to Earth. Since then, the geotechnical properties of this lunar regolith, as it is known, have been extensively characterised. However, it is not possible to conduct extensive research using the limited amount of lunar regolith collected during the former Apollo and Luna missions. As a result, there is a pressing need to manufacture large quantities of lunar regolith simulants on Earth to conduct such research.

The Andy Thomas Centre for Space Resources (ATCSR) at the University of Adelaide is a hub for interdisciplinary research on space exploration and colonisation. The ATCSR boasts a unique lunar simulation laboratory, known as Exterres, which contains a catalogue of simulants, including approximately one-tonne of mixed anorthosite and basalt (MAB-1), as well as smaller quantities of lunar highland (LHS-1) and lunar mare (LMS-1) simulants. These lunar simulants were acquired from the Center for Lunar & Asteroid Surface Science (CLASS) Exolith Lab at the University of Central Florida (UCF). The mineralogy of these simulants can be found in Exolith's datasheet (2022a, 2022b) and a summary is shown in Table 2. It is, therefore, of the utmost importance to compare the characteristics of the existing lunar simulants with those of the actual lunar soil.

Table 2. Mineral composition of lunar simulants LHS-1, MAB-1 and LMS-1.

Component	Weight %		
	LHS-1	MAB-1	LMS-1
Anorthosite	74.4	75.0	19.8
Glass-rich basalt	24.7	25.0	32.0
Ilmenite	0.4		4.3
Olivine	0.3		11.1
Pyroxene	0.2		32.8

2 LABORATORY TEST SUMMARY

A series of geotechnical laboratory tests was conducted to measure the geotechnical properties of the lunar simulants i.e. LHS-1, MAB-1 and LMS-1. The test procedures conformed to those outlined in the relevant Australian standards. To ensure the accuracy and reproducibility of the results, several experiments were repeated multiple times. The differences between these simulants and actual lunar regolith were highlighted. The results were also compared with Exolith lab's datasheet (2022a, b) to ensure the accuracy and reproducibility of the results. Tests were conducted under normal earth atmospheric pressure and an indoor temperature range of 22 ± 3°C, as well as a humidity of approximately 40 ± 10% during October to January. It is important to note the limitations of these tests due to the lack of a vacuum or lunar environment and further research is needed to evaluate environmental effects.

2.1 *Particle size distribution*

One of the key characteristics that significantly affect a soil's behaviour, such as strength and compressibility, is its particle size distribution (Carrier 1973). The continual impact of meteoroids, from large to extremely small, on the Moon's surface has resulted in the formation of a well-graded, silty sand-sized material called lunar regolith (Carrier III et al. 1991), as mentioned previously. A series of tests was performed to determine the particle size distribution of lunar simulants in accordance with AS 1289.1.1 (Standards Australia 2001), AS 1289.3.6.1 (Standards Australia 2009) and AS 1289.3.6.3 (Standards Australia 2020c). The results of these measurements are summarised in Figure 1.

Figure 1 demonstrates that the dry-sieve results from the present study agree well with the dry-sieve results presented by Exolith Lab. (2022a, b), which were performed using the relevant ASTM standards. Note, that when compared to the results obtained by using a laser diffraction particle size analyzer (CILAS 1190), there are significant discrepancies. Farries et al. (2022) carried out extensive research on the same simulants as examined in the present paper. The authors measured the particle size distribution using a Malvern Mastersizer 2000 device and have reported their results on LHS-1 to be similar to those of Exolith's. It is suggested that the dry sieving method has limitations and may not provide an accurate representation of the particle size distribution of these simulants, as the fine particles tend to adhere to the larger particles.

According to the Unified Soil Classification System (USCS), geotechnical engineers only differentiate between well-graded and poorly graded coarse-grained soils, such as sand. This determination is based on the coefficient of uniformity, C_u, and the coefficient of curvature, C_c which are defined in Eq. 1 and Eq. 2:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{D_{30}}{D_{60} \times D_{10}} \tag{2}$$

where D_{60}, D_{30} and D_{10} refer to particle-size diameters corresponding to 60, 30 and 10 percent passing, respectively. As is well known, a soil is classified as well-graded if it contains less than 12% fines, $C_u \geq 6$ and C_c is between 1 and 3. If $C_u < 6$ or $C_c < 1$ or $C_c > 3$, then it is classified as poorly graded (Carrier III 2003). Carrier III (2003) examined the particle size distribution of an average of 350 samples from the Apollo program and Luna 24. The main findings indicate that the lunar regolith broadly consists of medium sand to fine silt and it is very close to the

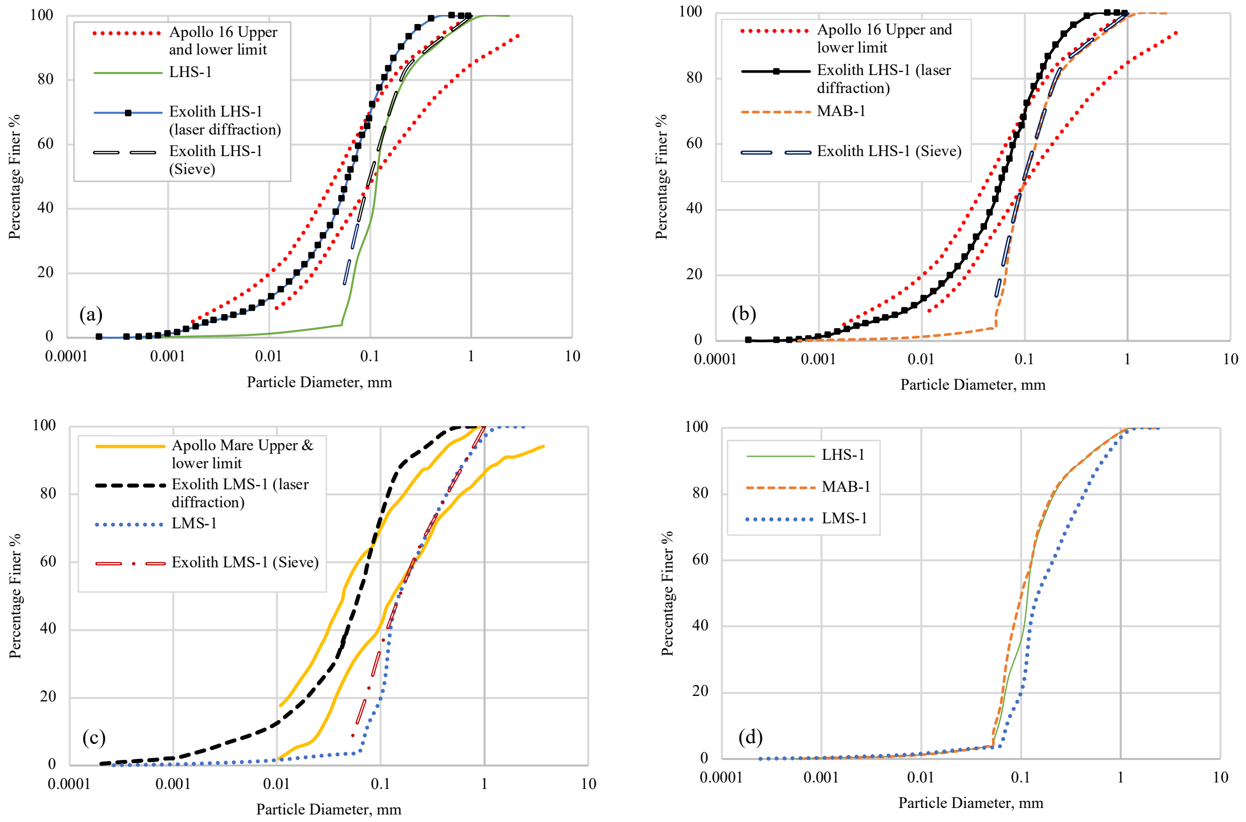

Figure 1. Comparison of particle size distributions between: (a) Apollo 16 – upper and lower limits (Venugopal et al. 2020), Exolith LHS-1 (laser diffraction), Exolith LHS-1 (Sieve) and LHS-1; (b) Apollo 16 – upper and lower limits, Exolith LHS-1 (laser diffraction), Exolith LHS-1 (Sieve) and MAB-1; (c) Apollo Mare - upper and lower limits (Carrier 1972), Exolith LMS-1 (laser diffraction), Exolith LMS-1 (Sieve) and LMS-1; (d) LHS-1, MAB-1 & LMS-1.

boundary between silty sand (SM) and sandy silt (ML), and is slightly on the sandy silt side. The range of the median particle size of the lunar regolith is 40 – 130 µm, C_u is 8.7 – 30 and C_c is between 0.7 – 2.0 (Carrier III 2003). The relevant geotechnical particle size parameters are shown in Table 3.

Table 3. Particle size parameters.

	D_{50} (mm)	C_u	C_c
Lunar Regolith (Carrier III, 2003)	0.072	16	1.2
MAB-1	0.101	2.33	0.75
LHS-1	0.117	2.20	0.97
LMS-1	0.149	2.92	0.84

As per the USCS, all of the tested lunar simulants are classified as silty sand (SM) and poorly graded. Figure 1 suggests that, in the dry-sieving method, the smaller particles tend to form clumps, where LHS-1 appears to have smaller particles below 105 µm, whereas MAB-1 has smaller particles below 75 µm. In contrast, LMS-1 has fewer particles in the range of 20 – 150 µm when compared to the Apollo Mare regions.

2.2 *Specific gravity*

The specific gravity of a solid is defined as the ratio of the mass of the soil to the mass of an equal volume of pure water at a specific temperature. The specific gravity of lunar regolith can vary depending on the proportion of different minerals, such as basalts, anorthosite, breccias, agglutinates, and glasses. Typically, the specific gravity of lunar regolith ranges from 2.3 to 3.5. Carrier III et al. (1991) recommended that the specific gravity of lunar regolith is considered to be 3.1 for scientific and engineering analyses. To determine the specific gravity of simulant samples, the vacuum pycnometer method outlined in AS 1289.3.5.2 (Standards Australia 2002) was used. In this method, soil particles that passed through a 2.36mm sieve were used to calculate the specific gravity. Extreme care was taken to remove all entrapped air when the volumetric flask containing the regolith and water was subjected to a vacuum (Das 2021). This test was conducted six times for each simulant, and the average of the results is shown in Table 4.

Table 4. Specific gravity test results.

	Simulant		
	LHS-1	MAB-1	LMS-1
University of Adelaide	2.81 ± 0.03	2.79 ± 0.03	2.98 ± 0.03
Exolith (Easter et al. 2022)	3.22 ± 0.24	–	3.03 ± 0.27

According to Carrier III et al. (1991), the ranges of specific gravity values of lunar regolith are between 2.30 to 3.50. The specific gravity of the lunar simulants used in this study was found to be within the range of values reported by Carrier III et al. (1991) but lower than the value reported by Exolith Lab. This discrepancy may be attributed to the variations in the testing procedures adopted. The lunar simulants used in this study do not include agglutinate particles, therefore the variations are consistent with the recommended value of specific gravity of lunar regolith. The obtained results are also very similar to those obtained by Joshi (2022), who also tested Exolith's LHS-1 and LMS-1 simulants.

2.3 *Minimum and maximum density*

In general, the minimum density of the soil is achieved when the grains are arranged in the loosest possible configuration, resulting in the highest void ratio. This is particularly relevant for the top layer of in situ lunar regolith, as the minimum density is often found at the surface (Long-Fox et al. 2022). On the other hand, the maximum density of soil is reached when the particles are packed as densely as possible, with the void ratio at its lowest. The minimum and maximum densities of lunar simulant were determined using the methodology outlined in AS 1289.5.5.1 (Standards Australia 1998). This involved, for the minimum density, measuring the volume of three known mass samples after a gentle inversion in a graduated cylinder and mechanical agitation for the maximum density. The average of these three measurements is displayed in Table 5.

Table 5. Minimum and maximum density test results (g/cm^3).

Simulant	University of Adelaide		Exolith Lab (Long-Fox et al. 2022)	
	Min	Max	Min	Max
LHS-1	1.47	2.02	1.27	1.87
MAB-1	1.45	2.00	–	–
LMS-1	1.54	2.13	–	–

As reported by Carrier III et al. (1991) the ranges of minimum and maximum densities of lunar regolith are between 0.87 – 1.30 g/cm^3 and 1.51 – 1.93 g/cm^3 respectively. The minimum and maximum densities of the lunar simulants are found to be greater than those of the lunar regolith because the latter contains intragranular, intergranular and subgranular porosity (Carrier et al. 1991). Using the values of the maximum (ρ_{max}) and minimum (ρ_{min}) densities, the corresponding values of the minimum (e_{min}) and maximum (e_{max}) void ratios, were determined from the following relationships which are expressed in Eq.3 and Eq.4:

$$e_{min} = \frac{G_s \times \rho_w}{\rho_{max}} - 1 \tag{3}$$

$$e_{max} = \frac{G_s \times \rho_w}{\rho_{min}} - 1 \tag{4}$$

According to Carrier III et al. (1991), the ranges of e_{min} and e_{max} values of lunar regolith are between 0.67 – 0.94 and 1.21 – 2.37 respectively. In this paper, the maximum void ratios of LHS-1, MAB-1 and LMS-1 were calculated to be 0.93, 0.94 and 0.88 respectively, whilst the minimum void ratios of LHS-1, MAB-1 and LMS-1 were found to be 0.40, 0.41 and 0.36 respectively. The similarity in the minimum and maximum densities of LHS-1 and MAB-1 can be attributed to their very similar mineralogy and particle size distribution.

2.4 *One dimensional compression*

The compressibility of lunar regolith is an important parameter for the design and performance of lunar infrastructure, as well as rover and lander wheel-soil interaction, as it determines the change in volume or densification of the soil when a force is applied to it (Thannasi et al. 2021). The compressibility of soil is typically measured through a variety of tests, such as the oedometer test and the triaxial test. In this paper, the oedometer test measures the compressibility of soil under a constant rate of vertical deformation. This test can provide information about the compressibility behaviour of the soil, such as the compression index and the coefficient of compressibility.

The oedometer test was conducted in accordance with AS 1289.6.6.1 (Standards Australia 2020b) using an automated oedometer device to measure the compressibility of each of the simulant soils through a 1D compression test. To attain a minimal initial dry density, the simulants were packed as loosely as possible, to understand the effect of compressive loading at different densities. Due to the absence of moisture on the surface of the Moon, precautions were taken that all the necessary equipment and regolith were oven-dried prior to testing. The results of the compression testing are shown in Figure 2, which indicates a two-stage compression process. The first stage involves particle slippage and reorientation to fill voids under low-stress or low-density conditions. The second phase occurs when the applied loading and confining pressure increases, causing distortion or breakage of particles, typically near the point of contact. The compression index (C_C) of the lunar regolith was determined and reported by Carrier III et al. (1991) to vary between 0.01 and 0.3. This very large variation is due to the variability in particle size and variations in the material at different locations on the lunar surface.

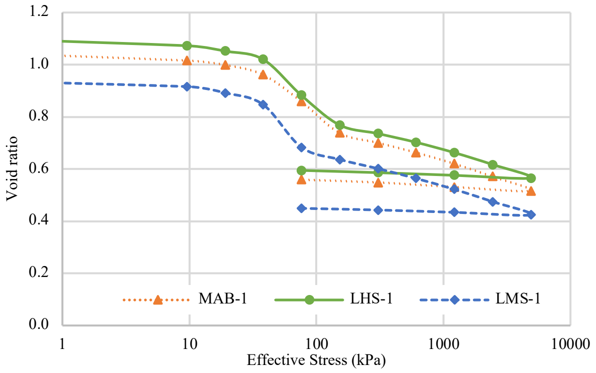

Figure 2. Void ratio vs effective stress.

The values of C_C are obtained from Eq. 5, where e_1 and e_2 are the void ratios corresponding to the applied pressures P_1 and P_2, respectively.

$$C_C = \frac{e_1 - e_2}{\log\frac{P_2}{P_1}} \tag{5}$$

The compressibility of the simulants LHS-1, MAB-1 and LMS-1 are found to be 0.134, 0.121 and 0.154 respectively at the range of stress of 76 kPa. These values corresponding to the lunar simulants fall within the expected range of lunar regolith. Carrier III et al. (1991) stated that lunar regolith is more compressible than that of a crushed basaltic lava simulant. This is due to the presence of irregular, fragile particles that crush under relatively low confining stresses. As seen is Figure 2, there is a dramatic drop in void ratio at around 20 – 80 kPa in all three simulants, which is likely caused by fine particle slippage or rearrangement and fragmentation of the particles.

2.5 *Proctor compaction testing*

Compaction is an efficient way to increase the density of the soil through the addition of mechanical energy. The Proctor compaction test is used to determine the maximum dry density that can be achieved at a standardised compactive effort, and it can be performed using either the standard or modified compaction test according to AS 1289.5.1.1 (Standards Australia 2017a) and AS 1289.5.2.1 (Standards Australia 2017b), respectively. This test involves removing air from the voids by rearranging and fragmenting the particles. The energy is added to the soil mass by dropping a hammer of standard weight and dimensions onto the soil. The standard and modified Proctor tests adopt hammers 2.7 and 4.9 kg in weight, and drop heights of 300 and 450 mm, respectively. The soil is compacted in a 1-litre mould applying 25 blows to each of three and five layers for the standard and modified tests respectively. The purpose of this test is to determine the densities that can be achieved on the Moon by applying compactive effort consistent with that adopted on Earth.

To evaluate the compaction of the simulant under lunar conditions, the height of the hammer is reduced to 1/6th of that specified by the test (i.e. 50 mm) to simulate the Moon's gravity relative to that of the Earth. The compaction energies associated with the standard and modified Proctor test are 596 kJ/m^3 and 2703 kJ/m^3 respectively and for the 1/6th standard test is approximately 100 kJ/m^3. The results are shown in Table 6. It is observed from the results of compaction test lunar mare simulant achieved higher dry densities than the other highland simulants i.e. LHS-1 and MAB-1. This is due to the greater specific gravity of LMS-1.

Table 6. Proctor test results.

Simulant	Proctor Test	Max. Dry Density (g/cm^3)
LHS-1	1/6th Standard	1.82
	Standard	1.87
	Modified	1.95
MAB-1	1/6th Standard	1.78
	Standard	1.85
	Modified	1.94
LMS-1	1/6th Standard	1.98
	Standard	2.02
	Modified	2.09

2.6 *Direct shear testing*

The shear strength parameters of any given soil have a significant impact on ultimate bearing capacity, slope stability and trafficability (Das 2021). The Coulomb failure criterion is the most commonly used method to describe soil shear strength, which expressed in Eq. 6, where τ is the shear strength, σ is the normal stress on the failure plane, *c* is the cohesion of the soil, and ϕ is the internal of angle friction.

$$\tau = c + \sigma \tan \phi \tag{6}$$

A series of direct shear tests was performed to measure *c* and ϕ. The tests were performed in accordance with AS 1289.6.2.2 (Standards Australia 2020a), with a minimum of three repeated tests. For each simulant two normal loads, i.e. 50 and 100 kPa, were adopted to determine *c* and ϕ. The initial relative densities of the LHS-1, MAB-1 and LMS-1 simulants at the beginning of the direct shear tests were 15%, 21% and 30% respectively. The results are presented in Figure 3 and Table 7.

As per Carrier III et al. (1991), multiple tests were performed on lunar regolith samples, with the best estimate of the internal angle of friction and cohesion values from the Apollo missions being 30° – 50° and 0.1 – 1 kPa respectively, and the best estimate from the Surveyor mission is 35° – 37° and 0.35 – 0.7 kPa respectively.

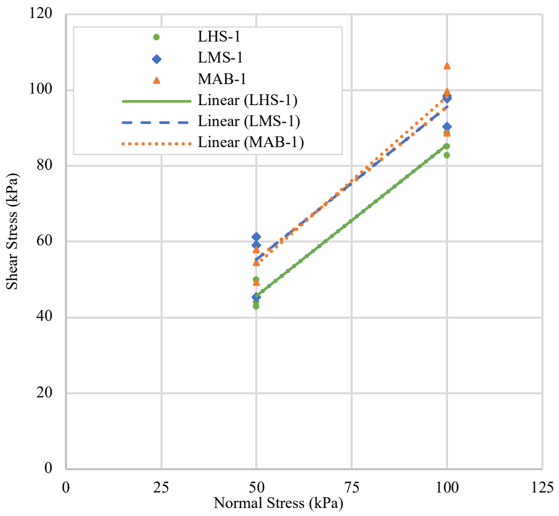

Figure 3. Shear stress vs normal stress.

Table 7. Shear strength values of lunar simulant.

Soil	*c* (kPa)	ϕ (°)
LHS-1	5.8	38.6
Exolith LHS-1	0.3	31.5
MAB-1	9.6	41.6
LMS-1	4.8	45.1
Exolith LMS-1	0.4	34.8

As can be observed, the values of the internal angle of friction of all of the lunar simulants are within the range of those reported for lunar regolith. The higher value of the cohesion is because the actual lunar regolith was tested during the Apollo and Luna missions in the lunar environment and with very low stresses applied. According to Carrier III et al. (1991), when the laboratory tests were complete, they yielded different values because the fragile particles tended to crush, resulting in a lower measured shear strength. It is important to note that different normal stress ranges were used in this study (i.e. 50 and 100 kPa) compared with Exolith (0.1–0.67 kPa) and Carrier III et al. (1991) (≤ 10 kPa), and this may be one of the reasons for obtaining different cohesion and frictional values; another may be the non-linear nature of the failure surface.

2.7 *Triaxial testing*

The triaxial test is another widely used method for determining the shear strength parameters of soils. In this study, the triaxial test was applied to the three different lunar simulants. The test involved preparing a cylindrical soil specimen, 50 mm in diameter and 100 mm in height, by carefully placing the loose simulant inside a rigid tube incorporating a rubber membrane. The relative densities over which the LHS-1, MAB-1 and LMS-1 simulants were tested ranged from 14 to 88%. The tests were conducted in accordance with AS 1289.6.4.2 (Standard Australia 2016), with some modest variations; the most notable being that compressed air was used instead of water to apply the confining pressure to the samples and, because the specimens were dry, pore pressures were not considered.

The test results are summarised in Figure 4 and show that the lunar simulants had negligible cohesion values, as reported by Millwater et al. (2022), and a range of internal angles of friction of 42° – 52° between relative densities of 14 – 18% were obtained.

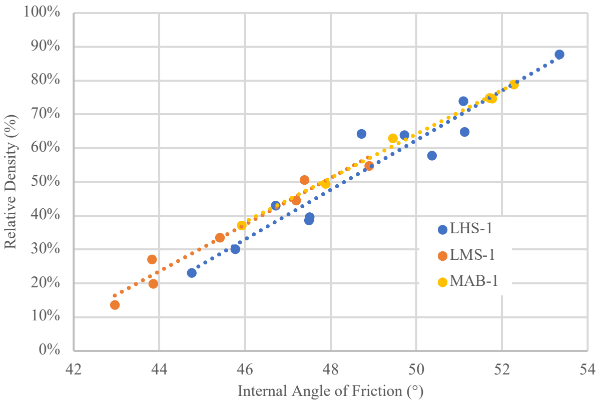

Figure 4. Internal angles of friction at various relative densities.

The results are consistent with those obtained using the direct shear test above, as well as those reported by Mitchell et al. (1972, 1974), who found cohesion values in the range of 0.1 – 1 kPa and internal angles of friction in the range of 30° – 50°, based on samples from the Apollo Missions. The results for both LHS-1 and MAB-1 were comparable, likely due to their similar mineral compositions. Using least squares regression, the relationship between the internal friction angle, ϕ, and relative density, *RD*, for the three simulants can be approximately described by the following linear relationship which is expressed in Eq. 7:

$$\phi = 1.396\,RD + 41.09 \tag{7}$$

3 CONCLUSIONS

In this study, the geotechnical properties of the lunar simulants LHS-1, MAB-1 and LMS-1 have been quantified and compared against the results of actual lunar regolith and other published results. Based on the results obtained, the following conclusions can be drawn:

- MAB-1 is a reasonable and cost-effective substitute for the LHS-1 simulant. The LHS-1 is around six-times more expensive than MAB-1. In terms of mineralogy, MAB-1 is very similar to LHS-1; the only difference being that LHS-1 contains pyroxene, olivine and ilmenite. The proportion by mass of these minerals is less than 1% in total. Based on this study, it is observed that the absence of these minerals resulted in negligible differences between the geotechnical properties of MAB-1 and LHS-1.
- The particle size distributions varied significantly, which is most likely due to the different testing methods. The dry-sieve method has limitations as fine the particles tend to adhere to coarser particles, thus distorting the results. When compared with the results from the laser diffraction methods, the particle size distribution of LHS-1, MAB-1, and LMS-1 agree well with those obtained from actual lunar regolith, and fall within the range of Apollo 16 samples (the only Apollo mission to the lunar highlands) for LHS-1 and MAB-1 and within the range of mare lunar regolith for LMS-1.
- The presence of mineral fragments, breccia, glass, and agglutinates affect the specific gravity of lunar regolith. The differences in testing methods adopted in the present study and by others were found to affect the results. The specific gravity of the lunar simulants used in this study was found to be within the range of values reported by Carrier III et al. (1991), who used actual lunar regolith, and Joshi (2022), who used a pycnometer and similar simulants used in this study, but lower than the values reported by Easter et al. (2022).
- To account for the reduced gravity on the Moon, the drop height, and hence potential energy, associated with the Proctor compaction tests was reduced to 1/6th of that specified by the standard procedures. The results of LHS-1 and MAB-1 are similar for all of the different compactive efforts applied. However, LMS-1 yielded higher dry densities due to its higher specific gravity.
- The minimum density of the lunar regolith was found to be less than all of the lunar simulants examined because the lunar regolith contains intragranular, intergranular and subgranular porosity. The maximum density of the simulants is within the range of lunar regolith.
- The compression index of the lunar simulants falls with in the reported range of lunar regolith. The large variation found between the range of compression indices obtained and those reported for lunar regolith, is likely due to the presence of agglutinates in the regolith. Further compression tests will be needed to predict the load-settlement behaviour of the simulants at different relative densities.
- The triaxial test results showed that all three simulants had negligible cohesion values and a range of internal angles of friction between 42° – 52° for a relative density range of 14 – 88%. These results agree well with previous studies on lunar regolith.

The geotechnical properties of all three simulants tested in this study – i.e. highland (LHS-1), mixed anorthosite and basalt (MAB-1) and mare (LMS-1) – differ from those of actual lunar regolith, since the lunar simulants were tested in a terrestrial context, as well as differences in the particle composition, as stated above.

4 ACKNOWLEDGEMENTS

This work has been supported and funded by the University of Adelaide's Andy Thomas Centre for Space Resources (ATCSR). The authors would also like to acknowledge the help and support of Mr. Kevin Farries and Mr. Gary Bowman from the University of Adelaide for their assistance with the testing presented.

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