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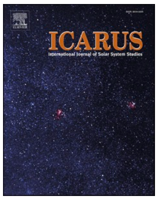

Geotechnical laboratory testing of lunar simulants and the importance of standardization

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ABSTRACT

A comprehensive program of geotechnical index tests performed on two regolith simulants, namely LHS-1 and LMS-1, are presented and discussed in this study. The index tests included a 2D analysis of particles shapes and measurements of grain density, particle size distribution, plastic and liquid limit, thermal conductivity, and maximum and minimum dry density. The detailed testing methodologies are provided, and their results are discussed and compared with data available in the literature from similar tests on the same regolith simulants. Additionally, a thorough analysis of the data in contrast with data of lunar soils is presented. The observed spread on the index tests results is explained by the indiscriminate use of different procedures, regolith mass, and methodologies across different laboratories and highlight the importance and urgency for planetary scientist to agree on best practices in geotechnical testing of regolith and extra-terrestrial simulants.

List of notations

C	clay content
C_u	coefficient of uniformity
C_c	coefficient of curvature
D	diameter
D_r	relative density
D_{10}	grain diameter at 10% passing
D_{30}	grain diameter at 30% passing
D_{60}	grain diameter at 60% passing
e	void ratio
e_{max}	maximum void ratio
e_{min}	minimum void ratio
FC	fines content
G_s	specific gravity of solid particles
H	height
M	initial wet mass of soil
M_s	mass of solids
PSD	particle size distribution
r	roundness
Sa	sand fraction
Si	silt fraction
TCd	thermal conductivity dry
TCm	thermal conductivity moist
w_L	liquid limit
w_P	plastic limit
ρ_s	unit weight of solid particles
ρ	sphericity
ρ_{max}	maximum dry density
ρ_{min}	minimum dry density
ρ_d	in situ dry bulk density
ρ_s	grain density
ρ_w	density of water = 1 g/cm^3

1. Introduction

The surfaces of many celestial objects, including the Earth's Moon, Mars and many other celestial bodies, are covered in a layer of unconsolidated dust, soil, and rock, known as regolith. As humanity prepares once again for manned missions and sustained development of the lunar (and Martian) surface, of broad interest right now is the development of in situ resource utilization (ISRU), which aims to enhance space mission capabilities by utilizing resources extracted from local regolith. Extraction of these resources and their conversion to useful products are

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dependent on engineering processes (excavation, trafficability, etc.) and are governed by regolith physical properties. Over the next decades, the creation of a space industry around ISRU is likely. This industry will require infrastructure development on the lunar surface, and the thorough characterization of regolith will be invaluable for the safe design and performance of human or robot-made structures, rovers, launch pads, living quarters, or any other needed infrastructure. Additionally, in order to advance the understanding of celestial mechanics in general, the planetary science community needs the means to characterize regolith in a systematic and reproduceable manner.

As on Earth, a strong knowledge of the mechanical properties of the surface regolith is critical to ensure safe construction and maintenance of infrastructure at the lunar surface, minimize geo-risks and hazards, and enable safe and effective resource extraction. However, the mechanical properties and behaviour of the lunar regolith differ to that of Earth, due to extraordinary differences in regolith formation processes, mineralogy, weathering, erosion, and environmental conditions (e.g., low gravity, low moisture, and extreme temperature fluctuations). Due to the scale of testing of equipment, infrastructure and systems that are being tested on Earth, scientist require much larger quantities of lunar soil than the amount of returned material that is currently available. Extraterrestrial simulants are crucial for various scientific studies and experiments related to astrobiology and the search for extraterrestrial life. Simulants are often designed to replicate the physical and chemical properties of extraterrestrial environments, such as the surface of Mars or the icy moons of Jupiter (i.e., Duri et al., 2022). To address the issue of limited amounts of returned lunar soil, lunar soil simulants were developed to reproduce certain characteristics of the regolith, specifically the mechanical and geotechnical properties in certain simulant examples.

Geotechnical index tests on lunar regolith samples were performed in the 1960s and 1970s, and the most comprehensive summary is given in Carrier et al. (1991), though the amount of regolith used on many of those early tests is indisputably small, and as shown in previous studies, the mass used to obtain geotechnical parameters does matter (i.e., Easter et al., 2022). Recently the use of lunar regolith simulants is gaining attention and studies reporting a variety of index tests are being published (see e.g., Stockstill-Cahill et al., 2022; Long-Fox et al., 2023; Yin et al., 2023, among others).

The primary objective of the current study is to add to the growing body of knowledge regarding lunar regolith simulant behaviour. This is done from the point of view of geotechnical testing and analysis using index tests. Index tests are the basis to investigate the mechanical response of regolith (or soil), and it is imperative to characterize properly the most basic parameters in a consistent and systematic way to minimize errors that can propagate into more advanced test results (e.g., a triaxial compression test). Index properties have a direct effect on measured regolith mechanical properties (such as compressibility, stiffness, shear strength, ice content, thermal conductivity, shear wave velocity, dielectric constant, etc.), hence the importance of them. In this study, a series of geotechnical index tests are performed on two popular lunar regolith simulants, and the results are compared to the existing literature produced by other laboratories on simulants and real lunar regolith. The simulants tested are manufactured to be representative of lunar highlands and lunar mare regolith.

A secondary objective of this study is to call attention to the lack of standardization in geotechnical testing of extra-terrestrial soil and simulants. This is in contrast to the common use of international testing standards used for normal routine terrestrial applications to ensure scientific repeatability and ensure safe engineering design. Through a comparison of the existing literature and tests performed, there is a lack of consensus about the standards, methods, techniques, regolith mass to be used, and best procedures that shall be used to obtain consistent and comparable results among the planetary research and industry communities working with regolith simulants. The results obtained in this study highlight the importance of committing to the use of relevant

Table 1
Geotechnical index testing programme and standards followed.

Test	Symbol	Units	Regolith simulants		Standard used
			LHS-1	LMS-1	
Roundness	r	–	0.60	0.62	Krumbein and Sloss (1963)
Sphericity	ρ	–	0.32	0.31	
Unit weight of solid particles	γ_s	(kN/m^3)	27.0	29.8	ASTM D854; ISO 17892-3 ISO, 2015
Grain density	ρ_s	(g/cm^3)	2.75	3.04	
Particle size distribution	PSD	–	–	–	
Diameter for which 10% finer	D_{10}	(mm)	0.013	0.014	
Diameter for which 30% finer	D_{30}	(mm)	0.035	0.051	
Diameter for which 60% finer	D_{60}	(mm)	0.102	0.186	
Sand fraction	Sa	%	56.7	66.8	
Silt fraction	Si	%	43.0	30.6	
Clay fraction	C	%	0.3	2.6	
Fines contents, particles <63 μm in ISO (or < 75 μm in ASTM)	FC	(%)	43 (49)	33 (38)	ASTM D6913; ISO 17892-4
Coefficient of uniformity	C_U	(−)	0.92	0.99	
Coefficient of curvature	C_C	(−)	7.8	13.7	
UCSC Classification (ASTM)	–	–	SP-SM	SW-SM	
Soil description after NGF (2011)	–	–	MATERIAL, sandy, silty	SAND, fine to medium, silty	
Plastic limit[1]	w_P	(%)	NA	NA	ASTM D4318–17
Liquid limit[1]	w_L	(%)	32	27	
Thermal conductivity (moist)	TCm	(W/mK)	1.10	–	ASTM D5334–14
Thermal conductivity (dry)	TCd	(W/mK)	0.22	0.18	
Maximum dry density					
NGI in-house method	$\rho_{d,max,NGI}$	(Mg/m^3)	1.844	2.243	Lunne et al., 2019
NGI-Geolabs	$\rho_{d,max,N\text{-}G}$		1.986	2.155	Knudsen et al., 2020
DIN (two-prong method)	$\rho_{d,max,DIN}$		1.921	2.099	DIN-18126
Minimum dry density					
NGI in-house method	$\rho_{d,min,NGI}$	(Mg/m^3)	1.361	1.640	Lunne et al., 2019
NGI-Geolabs	$\rho_{d,min,N\text{-}G}$		1.460	1.610	Knudsen et al., 2020
DIN	$\rho_{d,min,DIN}$		1.450	1.610	DIN-18126
Minimum void ratio					
NGI in-house method	$e_{min,NGI}$	(−)	0.491	0.328	Lunne et al., 2019
NGI-Geolabs	$e_{min,N/G}$		0.384	0.382	Knudsen et al., 2020
DIN (two-prong method)	$e_{min,DIN}$		0.431	0.419	DIN-18126

(*continued on next page*)

Table 1 (*continued*)

Test	Symbol	Units	Regolith simulants		Standard used
			LHS-1	LMS-1	
Maximum void ratio (NGI)					
NGI in-house method	$e_{max,\ NGI}$	(−)	1.020	0.817	Lunne et al., 2019
NGI-Geolabs	$e_{max,\ N/G}$		0.883	0.850	Knudsen et al., 2020
DIN	$e_{max,\ DIN}$		0.896	0.850	DIN-18126

[1] Test performed on particles <63 μm, plastic limit not possible to obtain as silt particles are non-plastic.

standards for geotechnical testing and the inherent limitations of some methods to obtain representative values of, for instance, relative density. This is particularly important, as it has implications for instance on the relative density, which is used later for advanced testing, from which strength and stiffness values are derived and used later for geotechnical engineering design. The research presented herein has been inspired by recent work performed at the Norwegian Geotechnical Institute (NGI) on relative density of terrestrial sands (see Lunne et al., 2019).

2. Materials and methods

2.1. Simulants tested

Due to the obvious difficulties related to sampling and transportation of copious quantities of lunar regolith, or any other extra-terrestrial regolith, regolith analogues or simulants are being used to investigate the physical, chemical, and mechanical behaviour of celestial bodies. There are several commercially available (or unavailable) lunar regolith simulants, for instance: the LHS-1 lunar highland and LMS-1 lunar mare simulants manufactured by Exolith Lab (Long-Fox et al., 2023), JSC-1 A and JSC-2 A simulants by the Orbital Technologies Corporation (Collins et al., 2022), OPRH2N highland and OPRL2N mare simulants by Off Planet Research, CSM-LHT-1 highland and CSM-LMT-1 mare simulants by Colorado School of Mines (space.mines.edu), OB-1 A highland simulant by Deltion, USGS NU-LHT-4 M highland simulant, or the EAC-1 A by the European Space Agency (Engelschiøn et al., 2020), among others. This research focusses on the regolith simulants LHS-1 and LMS-1.

The LHS-1 and LMS-1 simulants used are so-called high-fidelity mineral-based generic averages and are manufactured by the non-profit organization Exolith Lab from Florida, US (exolithsimulants.com). Exolith Lab produces the regolith simulants by mixing individual minerals and lithic fragments in varying proportions to match the reported lunar granulometry. The LHS-1 simulant is made from a mixture of greenspar anorthosite (74.4 wt%), glass 24.7%, ilmenite (0.4 wt%), pyroxene (0.3 wt%), and olivine (0.2 wt%), while the LMS-1 simulant is made by mixing anorthosite (19.8 wt%), glass and basalt (32.0 wt%), Ilmenite (4.3 wt%), pyroxene (32.8 wt%), and olivine (11.1 wt%) (see Yin et al., 2023).

2.2. Testing programme overview

A series of index tests were performed in this research to determine common regolith index properties such as the particle morphological characteristics, grain density (ρ_s), the particle size distribution (PSD), plasticity limits (plastic limit w_P and liquid limit w_L), thermal conductivity, and the minimum and maximum dry density ($\rho_{d,min}$ and $\rho_{d,max}$, respectively). All index tests were performed following internationally recognized standards, such as the American Standard of Testing Materials (ASTM) or the International Organization for Standarization (ISO), which are commonly used in geotechnical practice for terrestrial applications. Testing procedures are found in the individual standards, and any deviations are described herein in detail. In the case of the maximum and minimum dry densities (from which the maximum and minimum void ratios, e_{min} and e_{max}, are calculated), several other standard and non-standard – but well-documented proprietary methods – were also used. Table 1 provides an overview of the geotechnical index tests performed in this study, together with the individual standards and procedures followed.

3. Testing methods and procedures

3.1. Particle morphological characteristics

Two-dimensional (2D) particle shapes of grains were determined following the definitions of Krumbein and Sloss (1963), where particle shape is classified in terms of roundness (r) and sphericity (ρ). Roundness is defined by the average radius of circles that can be inscribed in the particle's convex corners divided by the radius of the maximum inscribed circle and it is the asymptotic shape of abrasion. Sphericity is defined as the ratio between the radius of the maximum inscribed circle and the radius of the minimum circumscribed circle. Particle morphological characteristics, such as r and ρ, are useful indicators of the formation and history of the granular material (see Santamarina and Cho, 2004), and help to understand, or even predict, the possible in situ packing and macro scale mechanical characteristics of regolith, such as thermal conductivity, strength, and stiffness anisotropy, internal friction angle, etc. To determine r and ρ of the sand size particles (63 μm – 2 mm according to ISO 17892-4), subsamples of LHS-1 and LMS-1 were sieved in ranges of sizes between 63 and 125 μm, 125–250 μm, and 250–500 μm. From each range at least 30 individual particles were photographed using an electro-microscope (Nikon type ellipse, LV100 POL up to 40× magnification). The obtained 2D images were then analysed using an in-house developed python script that uses a segmentation algorithm to identify and label each particle. The particle geometry measurement algorithm is based on a modified version of the algorithm proposed by Zheng and Hryciw (2015), the screening algorithm for convexity was upgraded at NGI to correctly identify inscribed circles on particles shapes and to minimize errors with respect to shape identification. Note that the estimated values of r and ρ were obtained in 2D.

3.2. Specific gravity

The grain density (ρ_s, or related specific gravity of the solid particles) is the ratio of the weight of the soil solids to the weight of water of equal volume, and is a useful parameter need to calculate other material index properties such as the void ratio and soil density. Typical values of ρ_s for most terrestrial regolith ranges between 2.6 and 2.8. ρ_s was determined by the pycnometer method (ASTM, 2016a), which is based on the determination of the difference in the volume of liquid required to fill the pycnometer with and without the sample material being present. The density of solid particles is calculated from the dry mass of the soil particles and the volume difference of the liquid required to fill the pycnometer volume. Two experiments are made, and the average of the two experiments is the reported unit weight, provided the difference in the two estimations is <0.3 kN/m^3.

3.3. Particle size distribution

The particle size distribution (PSD) influences the mechanical response of regolith to loads and fluid flow. PSDs are extremely useful for textural classification of regolith and for initial estimates of the mechanical engineering behaviour. PSD-based classification discretizes the regolith into gravel, sand, silt and clay sizes, depending on the average particle size (see for instance ASTM classification system, ASTM 2017). PSD curves in this study were obtained using the wet sieving method for the coarser fractions (ISO, 2018a, 2018b) and using the falling drop method (Moum, 1965) for the clay and silt fractions. Soils containing >5–10% silt and clay particles are usually wet sieved on a 63 μm sieve at NGI. The falling drop method is a sedimentation method based on Stoke's Law, where a small regolith sample of moist material is suspended in water, washed through a 63 μm (ISO, 2002) or 75 μm sieve (ASTM, 2017) before being poured into a sedimentation tube. Droplets from a certain depth in the sedimentation tube are sampled with a calibrated micropipette after certain time intervals and then ejected into a glass column containing an organic liquid with a slightly lower density (Moum, 1965). The time required for each droplet to fall a certain distance in the organic liquid is measured. The concentration of suspended particles in each droplet can then be read from a calibration chart developed at NGI (Moum, 1965).

3.4. Liquid and plastic limits

The physical and mechanical properties of fines can be further assessed by means of their behaviour with increasing water content. Regolith can change its state depending on its water content from solid, semi-solid, plastic and liquid (Budhu, 2010). The liquid limit, w_L, and plastic limit, w_P, are the highest and lowest water contents at which regolith can be found in a plastic state. In this study, w_L was determined on sieved samples of the fines content (FC) of each simulant following (ASTM, 2017b). It was impossible to measure w_P (ASTM, 2017b) because the FC contained non-plastic silt-size materials. The w_L measurement was performed using the Single Point method consisting of a 60 g standard Fall Cone device. When the cone penetration falls between 7.0 and 15.0 mm, the water content of the sample is determined and w_L is calculated.

3.5. Thermal conductivity

The thermal conductivity (TC) is the ability of materials to conduct heat. In regolith, TC is highly dependent on the moisture content, and gas or atmospheric pressure. Under Earth atmosphere, typical values for sand are ca. 0.26 to 3.01 $W{\cdot}m^{-1}\ K^{-1}$ depending on its composition and saturation (see i.e., Smits et al., 2010). TC has been measured on Moon regolith during the Apollo 15 and 17 missions (see Langseth et al., 1972, 1973), and values between $1.41{\cdot}10^{-2}\ W{\cdot}m^{-1}\ K^{-1}$ and up to $2.95{\cdot}10^{-2}\ W{\cdot}m^{-1}\ K^{-1}$ were recorded at 0.35 m and 2.33 m depth, respectively. More recently, TC measurements on the far side of the moon, have been reported by Xiao et al. (2022) and range from $1.53{\cdot}10^{-3}$ to $8.48{\cdot}10^{-3}\ W{\cdot}m^{-1}\ K^{-1}$ from 0 to 1 m depth, respectively.

The TC tests in this study were performed at atmospheric pressure following ASTM (2018) and ASTM (2022). To highlight the effect of water content, the LHS-1 simulant was tested moist and dry, while LMS-1 was tested in dry conditions only. Even though the herein presented measurements will not be representative for Lunar conditions, they may be valuable for investigating the use of regolith inside future planned Lunar base(s) under controlled environments and for research in ISRU applications.

3.6. Relative density

The relative density D_r is an index parameter that aims to quantify the degree of packing between the loosest and densest state of coarse-grained material (Budhu, 2010). The D_r concept is a widely used concept because it is linked to the strength and stiffness of regolith. There is a myriad of methods used worldwide to obtain ρ_{max} and ρ_{min} of granular materials, for instance following ASTM, the British standard, the German Deutches Institute for Nörmung (DIN), the Danish Dansk Geoteknisk Forening (DGF) Guidelines, the Japanese Standard (JIS) and in-house developed methods such as the Norwegian Geotechnical institute (NGI), Geolabs or many other proprietary methods based on modifications of the above listed methods. Values of ρ_{max} and ρ_{min} are used for the critical purpose of computing D_r of the granular material by:

$$D_r = \frac{\rho_d - \rho_{min}}{\rho_{max} - \rho_{min}} \left\{ \frac{\rho_{max}}{\rho_d} \right\}, \tag{1}$$

where ρ_d is the in situ dry bulk density of the material. D_r can also be expressed in terms of maximum void ratio (e_{max} or loosest condition) and minimum void ratio (e_{min} or densest condition), where the void ratio is calculated as

$$e = G_s \frac{\rho_w}{\rho_d} - 1 = \frac{\rho_s}{\rho_d} - 1, \tag{2}$$

where ρ_w is the density of water, and D_r is expressed as

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}}. \tag{3}$$

3.7. Methods to determine the maximum dry density

Methods used to determine the maximum dry density ρ_{max} (e_{min}) achieve the densest state of the material by applying energy in the form of tamping, tapping, rodding, or vibrating. If the energy applied is too high, there is a risk of crushing the particles and hence altering the PSD of the material. Additionally, standard methods used for terrestrial soil applications have limitations in their applicability with respect to the amount of FC. Industry standards require a total material mass between 11 kg (ASTM, 2016c) to a minimum of 300 g (DGF, 2001guidelines). Note that tests performed in the early 70's on lunar regolith from the Apollo and Luna missions used masses of about 5.5 g (median value for all studies) to masses as low as 0.96 g (Carrier et al., 1991), which are extremely low masses in comparison with their standardized terrestrial counterparts. The low mases used were driven by the scarcity of returned lunar samples and are far from what should be consider sufficient to obtain reliable and repeatable data. While the values obtained using Apollo samples are useful as a reference (not a benchmark), the use of larger masses, and current standard practices, will yield different results (see i.e., Easter et al., 2022, where it is shown that the mass used to investigate the effects of mineralogy and particle size on the angle of repose matters).

In this study we used the NGI in-house method (Lunne et al., 2019), the NGI-Geolabs method (Knudsen et al., 2020), and the DIN two-prong method (DIN, 1996). All tests were performed on dry regolith. A summary of these methods is provided herein for completeness. The NGI in-house proprietary method requires 500 g of soil, which is placed in thin layers in a brass mould (5 cm in diameter, D) and vibrated for 30 s using a 4.2 kN/m^2 pneumatic air hammer, the maximum FC allowed for terrestrial soils is 10%. The NGI-Geolabs method was derived from a thorough study on sands as a promising method that avoids particle crushing while achieving a consistent and systematic dense state. The NGI-Geolabs uses a plastic mould (D = 7 cm, 20 cm in height, H), where 500 g of material is placed in a single layer and vibrates the material using a vibration table with a vibration amplitude of 2 mm for 2 min without any surcharge, followed by 15 s with a surcharge load of 7 kPa. The DIN method used in this study comprises the use of a two-prong impactor and a mould (D = 71 mm and H = 112 mm), The regolith is placed in five layers, while the mould is struck horizontally 30 times per layer, afterwards a 0.5 kg loading plate is placed on the soil and the mould is struck again.

3.8. Methods to determine the minimum dry density

All methods used to determine ρ_{min} (e_{max}) in this study are based on the principle of retraction of a soil filled steel tube or funnel. The grains fill a mould as the tube or funnel is steadily retracted whilst keeping the lower end just above the newly emplaced soil so that the sample is *poured* into a loose state. As the principle to obtain ρ_{min} is essentially the same among the chosen methods, the differences between the methods

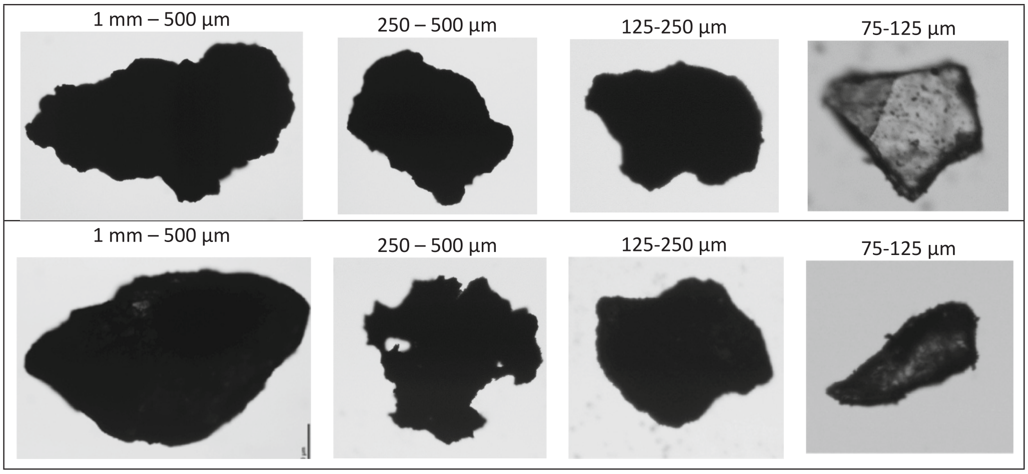

Fig. 1. Electro-microscope images of sand-sized particles of LHS-1 (top row) and LMS-1 (bottom row).

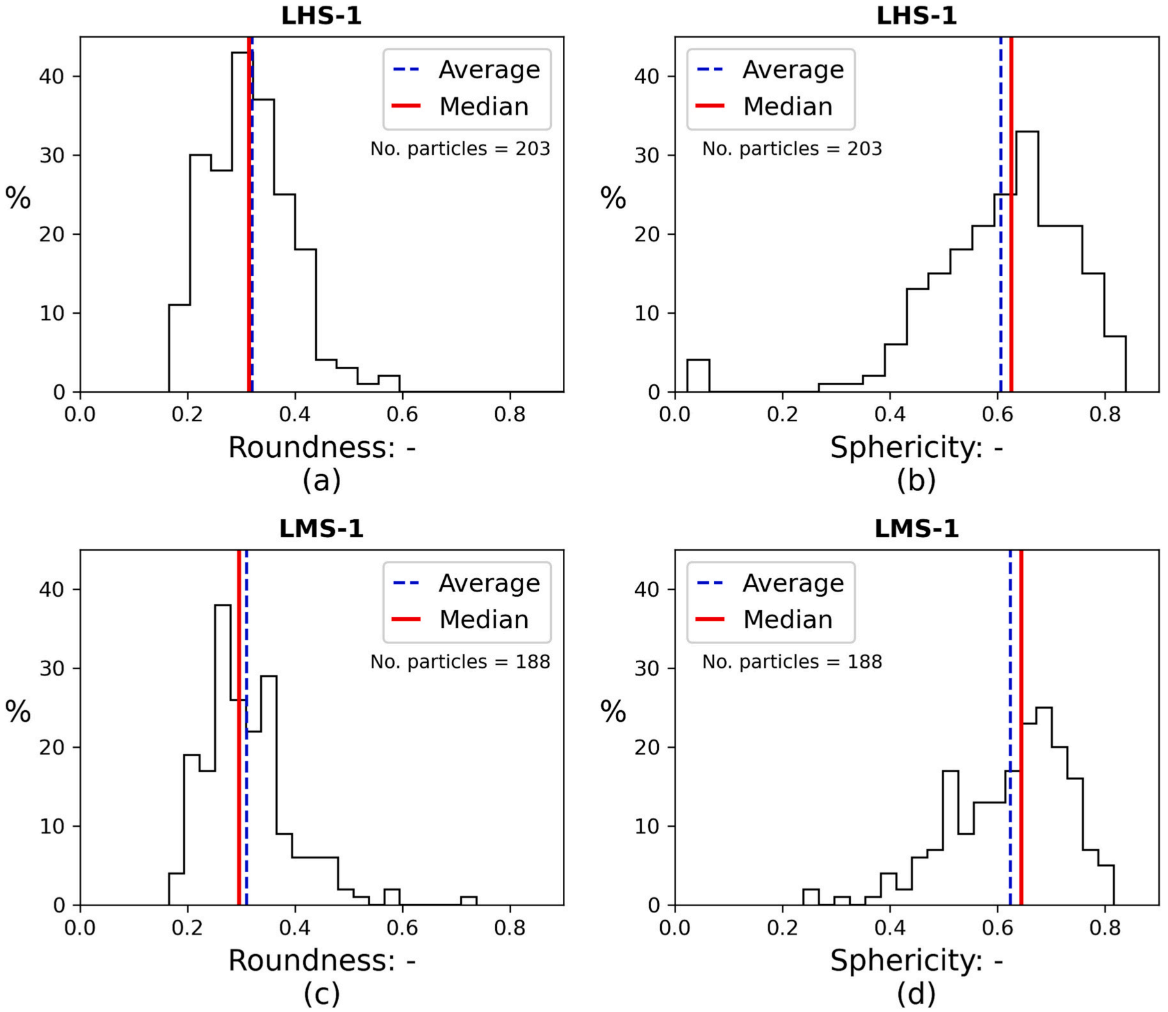

Fig. 2. Roundness and sphericity distributions of LHS-1 (a) and (b), respectively, and the same for LMS-1 (c) and (d).

are only related to the geometrical characteristics of the devices used. The NGI method uses a steel tube (D = 35 mm) and a mould of D = 72 mm and H = 50 mm. The NGI-Geolabs and the DIN methods share the same components, namely a D = 12 mm steel funnel and a D = 71 mm by 112 mm mould.

4. Experimental results

Two-dimensional images of sand-sized particles of LHS-1 and LMS-1 were used to obtain r and ρ particle shape parameters (Fig. 1). The mean values for LHS-1 particles are $r = 0.60$ and $\rho = 0.32$, while $r = 0.62$ and $\rho = 0.31$ for LMS-1. Note that both simulants have remarkably similar 2D

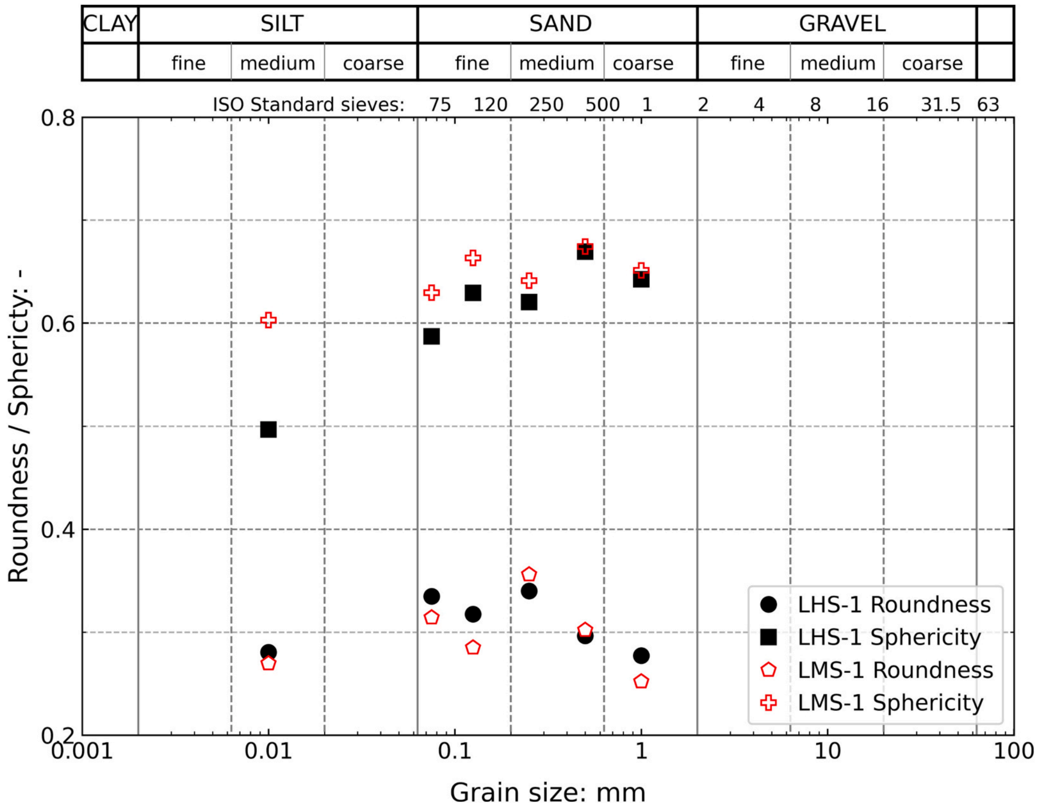

Fig. 3. Roundness and sphericity as a function of grain-size for LHS-1 and LMS-1 simulants.

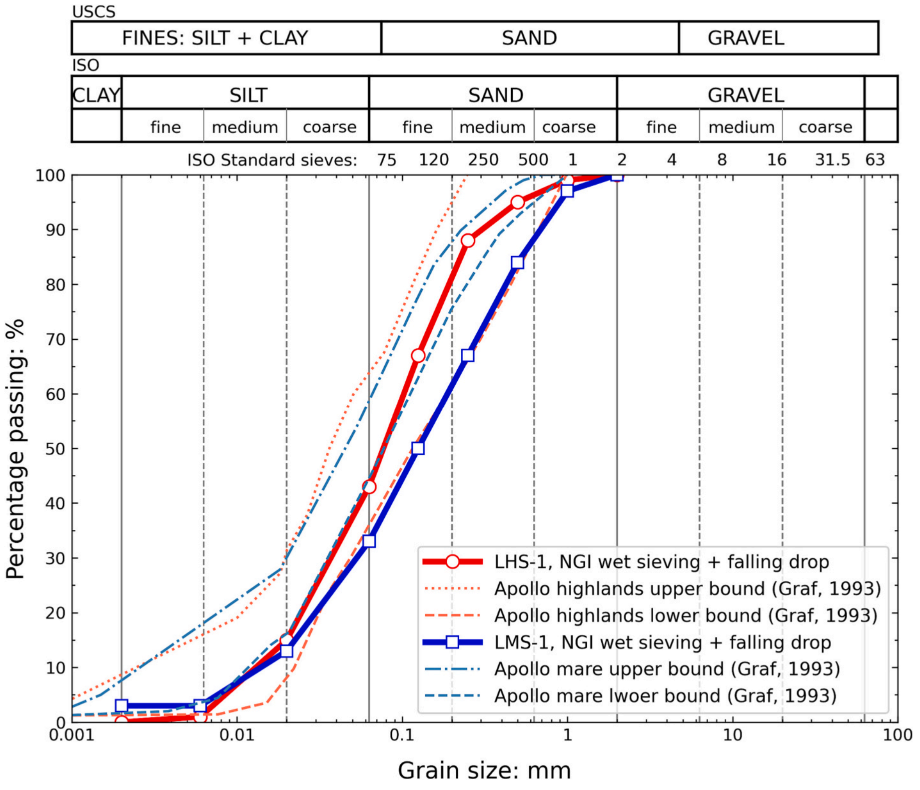

Fig. 4. Particle size distribution (PSD) curves of (a) LHS-1 and (b) LMS-1 together with lunar “key soils” sample upper and lower bounds from Highlands and Mare by Graf (1993).

Table 2
Mean particle shape parameters of LHS-1, LMS-1 and lunar regolith return samples.

Source	Regolith	Elongation	Aspect ratio	Roundness
Current study	LHS-1	1.49 (elongated)	0.70 (Moderately elongated)	0.60 (Rounded)
	LMS-1	1.46 (elongated)	0.72 (Moderately elongated)	0.62 (Rounded)
Lunar regolith Carrier et al. (1991)	Average (ranges)	1.35 (1.31–1.39) (Somewhat elongated)	0.55 (0.4–0.7) (Slightly to medium elongated)	0.21–0.22 (Subangular to angular)

roundness and sphericity values, which may result from the same preparation procedures used to manufacture these simulants.

Fig. 2 shows normalised (%) histograms of r and ρ for all investigated particles (203 and 188 particles for LHS-1 and LMS-1, respectively). The histograms represent skewed-to-the-left and skewed-to-the-right distributions for r and ρ, respectively. For an additional comparison between LHS-1 and LMS-1, Fig. 3 shows r and ρ values versus grain-size.

Values of ρ_s of the solid particles for LMS-1 is 2.75 and LHS-1 is 3.04 (Table 1). In addition, Fig. 4 shows the lower and upper bounds of the PSD curves of lunar regolith compiled by the lunar Soil Characterization Consortium (Graf, 1993). The LHS-1 curve obtained by wet sieving), falls within the upper and lower bounds of Apollo highland samples, while LMS-1 does not. The values of the particle size at 10%, 30% or 60% by weight (D_{10}, D_{30} and D_{60}, respectively) of particles having a smaller nominal diameter are presented in Table 1. Together with the fines content (FC) values for particles <63 μm, and the coefficients of uniformity ($C_U = D_{60}/D_{10}$) and curvature ($C_C = D_{30}^2/(D_{60} \cdot D_{10})$), LHS-1 is classified as Poorly Graded Sand according to ISO (2002) or Silty Sand (SP-SM) by ASTM (2017a), while LMS-1 is classified as Well Graded Sand or Silty Sand (SW-SM).

The w_L was determined using particles <63 μm, with values of 32 and 27 for LHS-1 and LMS-1, respectively (Table 1). It was not possible to determine the plastic limit of the simulants, which means that the fines are non-plastic. This is an important observation, as plasticity influences the strength and deformation behaviour of granular materials (e.g., useful when processing regolith with fluids). The thermal conductivity (Tc) of both simulants is in average 0.2 W/mK and the thermal resistivity is the inverse of Tc (Table 1). Note that there is an expected reduction of Tc with decreasing water content, by a factor of 5 (Table 1). The average values of ρ_{max} and ρ_{min} are 1.917 (±0.058) and 1.424 (±0.045) for LHS-1 and 2.165 (±0.059) and 1.620 (±0.014) for LMS-1. The mean values come from individual methods used in this study (Table 1).

5. Comparisons and discussion of results

5.1. *Particle morphological characteristics and particle size distribution*

The particle shape of lunar regolith particles was reported in the late 60's early 70's to be highly variable, "from spherical to extremely angular, but in general elongated and subangular to angular" (see Carrier et al., 1991). Lunar regolith particles are irregular and their reported average elongation, aspect ratio and roundness, in comparison with the average values obtained on LHS-1 and LMS-1, are given in Table 2. The elongation and aspect ratio of the simulants are greater than for the lunar regolith. Nevertheless, the roundness of both simulants is significantly higher than the reported values for Apollo regolith samples. It is peculiar that LHS-1 and LMS-1 have almost identical 2D-roundness, while LHS-1 has slightly lower values of 2D-sphericity than LMS-1 with particle size.

5.2. *Specific gravity*

Fig. 5 compares values of ρ_s obtained for LHS-1 and LMS-1 to other studies that have used the same method (pycnometer). Typical lunar regolith values (Carrier et al., 1991) are also presented. All values of ρ_s and their respective studies are presented in Table 3. Note that ρ_s results between NGI and Stockstill-Cahill et al. (2022) agree quite well for LHS-1, but the Yin et al. (2023) result does not. LHS-1 results obtained by NGI and Stockstill-Cahill et al. (2022) are lower than the reported lunar values (for Highlands and Mare) by Carrier et al. (1991) on Apollo samples. Note that even such a simplistic test as the pycnometer needs to

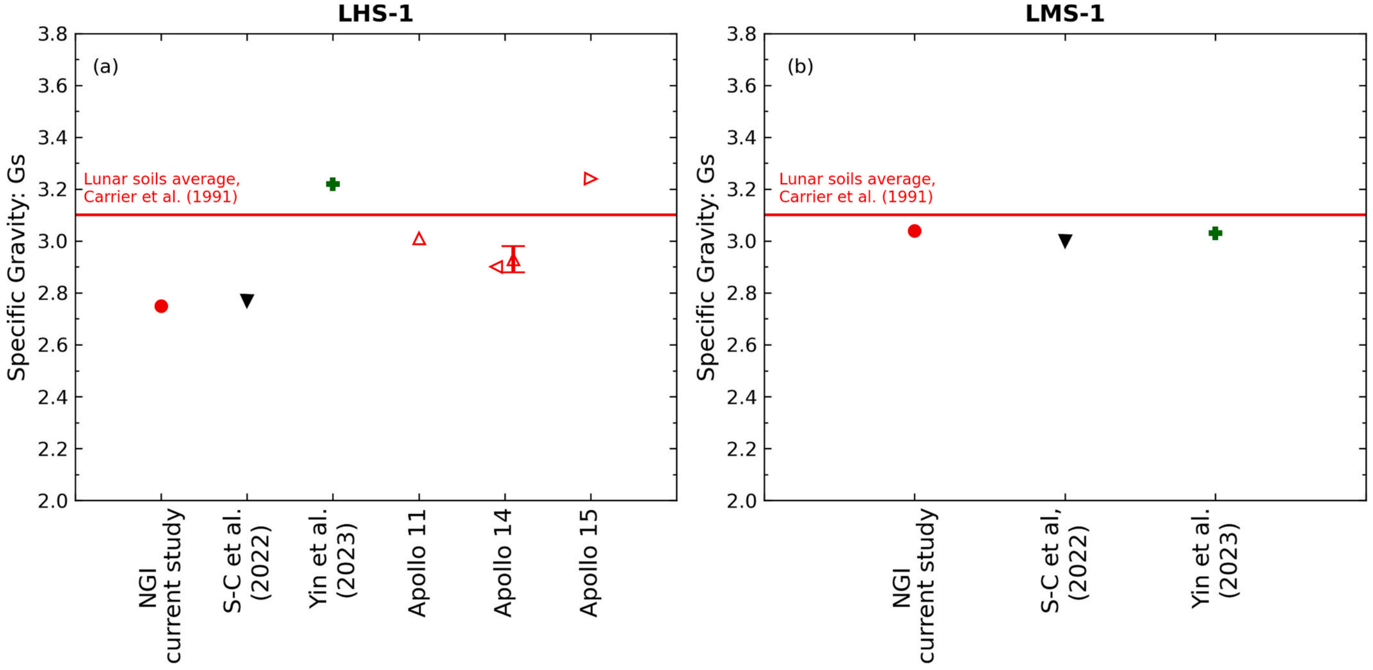

Fig. 5. Comparison of ρ_s for (a) LHS-1 and (b) LMS-1 by different studies in contrast with lunar soils by Carrier et al. (1991).

Table 3
Literature values of $\rho_{d,max}$, $\rho_{d,min}$ and ρ_s for LHS-1 and LMS-1 simulants and lunar regolith.

Source	Simulant/ Regolith	Minimum dry density	Maximum dry density	Mass of soil and standard used to determine $\rho_{d,min}$ and $\rho_{d,max}$	ρ_s (cm/ g^3)
		$\rho_{d,min}$ (g/cm^3)	$\rho_{d,max}$ (g/cm^3)		
Current study – NGI in-house	LHS-1	1.361	1.844	500 g of soil used	2.75
	LMS-1	1.640	2.243		3.04
Current study – NGI-Geolabs	LHS-1	1.460	1.986		2.75
	LMS-1	1.610	2.155		3.04
Current study - DIN	LHS-1	1.450	1.921	687 g for $\rho_{d,min}$ and 500 g $\rho_{d,max}$	2.75
	LMS-1	1.610	2.099		3.04
Long-Fox et al. (2023)	LHS-1	1.27	1.86	ASTM D4254–2016 conformal for $\rho_{d,min}$ and mechanically tapping 100 g of regolith for $\rho_{d,max}$	N/A
	LMS-1	1.47	1.95		N/A
Stockstill-Cahill et al. (2022)	LHS-1	1.38	1.56	1.3–1.3 Kg (cylinder of 943.9 cm^3), ASTM D-2049-1999 using a proctor cylinder and funnel for $\rho_{d,min}$, and surcharge load for $\rho_{d,max}$	2.77
	LMS-1	1.58	1.73		3.00
Yin et al. (2023)	LHS-1	1.39	1.91	1000 g	3.22
	LMS-1	1.56	2.06		3.03
Carrier et al. (1991)*	Apollo 11	1.36 (1.26)	1.80	5 g (565 g)	3.01
	Apollo 14	0.89 (±0.03) / 0.87 (±0.03)	1.55 (±0.03) / 1.51 (±0.03)	0.97 g / 1.26 g	2.90 (± 0.05) /2.93 (± 0.05)
	Apollo 15	1.10 (±0.03)	1.89 (±0.03)	0.96 g (developed for small quantities of regolith)	3.24 (± 0.05)

* Note that the mass of Apollo samples used are far below standard practices.

be properly performed, following strictly the ASTM (2016a) standard, to obtain repeatable results. The LMS-1 results are more consistent across the different laboratories. The values obtained on LHS by NGI and Stockstill-Cahill et al. (2022) seem more reliable since they agree on both simulants, but note that there can be internal variability among batches during simulant production, which could be a reason for the LHS discrepancy among the different studies.

5.3. Particle size distribution

The PSD curves for LHS-1 and LMS-1 obtained in this study are compared to other reported PSDs for the same simulants that were obtained at different laboratories using different methods (Fig. 6). Additionally, the range of upper and lower bounds for Highlands and Mare regolith from Graf's (1993) database are shown for reference. Long-Fox et al. (2023) reported PSDs obtained using laser diffraction (by volume), while Stockstill-Cahill et al. (2022) presented PSDs obtained by dry sieving using ASTM standard sieves. Exolith labs published datasheets for PSDs are also obtained by dry sieving. The lunar regolith PSD data compiled by Graf (1993) was obtained by dry sieving (Butler and King, 1974) or by a combination of dry sieving until 20 μm and below that size, particles were sized by analysing a dispersed grain mount with a computer-coupled optical microscope (McKay et al., 1974). From a visual inspection of the PSDs presented in Fig. 6, it is apparent that the method used to determine the PSD has a profound influence on the results. Hence, it is advocated for standardization of best practices within the ISRU research and industry community to avoid unnecessary spread and uncertainty in the results. A more thorough overview of the differences between the different PSDs is presented with the aid of Table 4 and Fig. 7, where particle sizes, percentages soil type, and grade curve characteristics are compared. In Fig. 7 the spread of the results for D_{10}, FC, C_c and C_u are plotted against Graf (1993) values for Highlands (Fig. 6a) and Mare lunar regolith (Fig. 6b). Values of D_{10} (Fig. 7a and e) and FC (Fig. 7b and f) obtained in the current study, and in Long-Fox et al. (2023) fit within the lunar regolith range for Highlands, while only Long-Fox et al. (2023) values are comparable to the range for Mare regolith. The values of Stockstill-Cahill et al. (2022) and Exolith Lab should be the values that should fit with Graf's (1993) database, as all used the dry sieving method. C_u values obtained by all methods fit in the Highlands range (Fig. 7c), and only the Stockstill-Cahill et al. (2022) value does not fit within the Mare range (Fig. 7g). Only C_c values obtained by Long-Fox et al. (2023) fit the Highlands range (Fig. 7d), and for the Mare, values of C_c of the current study fit within the range of expected values (Fig. 7h). It is important to note that the regolith simulants are manufactured such that their PSD fits within the range of lunar regolith, and the same standard method for obtaining PSDs should be used when comparing them, as different methods provide different PSD curves.

5.4. Maximum and minimum density

It is known (but unfortunately not well enough in the geotechnical community) that measurements of the maximum and minimum density are very much method dependent. Different equipment, different procedures, and different methods lead to a wide range of results, and, ultimately to unreliable measures of relative density (see Lunne et al., 2019 study on sands). Moreover, the concept of relative density itself becomes ambiguous, because small differences in $\rho_{d,max}$ or $\rho_{d,min}$ artificially stretch the 0 to 100 scale of D_r. Therefore, any small variation in the difference of $\rho_{d,max}$ -$\rho_{d,min}$ will result in a large variation of D_r, which yet again is motivation to standardize the best practices and develop methods that are applicable for lunar regolith. Rigorous, systematic and repeatable determination of $\rho_{d,max}$ or $\rho_{d,min}$ avoid the overestimation of strength and stiffness parameters, which are critical to safe geotechnical engineering design. As we show next, there is currently a lack of rigor when determining $\rho_{d,max}$ or $\rho_{d,min}$.

Fig. 8 shows the maximum and minimum dry density results obtained in this and other studies using the same LHS-1 and LMS-1 simulants; the values for lunar regolith are plotted for comparison. The measurements were obtained using NGI in-house procedures, the NGI-Geolabs method, the DIN standard described above. Moreover, Long-Fox et al. (2023) reported vales obtained using a procedure conformal to ASTM (2016b) - Method C for $\rho_{d,min}$. Long-Fox et al. (2023) obtained $\rho_{d,max}$ by mechanically tapping samples of 100 ± 5 g in a 100 mL graduated cylinder until no further volume reduction was observed. Values reported in the John Hopkins University study (JHU, by Stockstill-Cahill et al., 2022) were obtained following the superseded of ASTM (1999) D-2049 method that makes use of a large mould (943.9 cm^3) and a funnel for $\rho_{d,min}$, while $\rho_{d,max}$ was measured by vibrating the regolith in the same mould using a surcharge load. Yin et al. (2023) used ASTM (2016b) D4254 to determine the extreme values of dry density. The ρ_{min} was determined using 1 kg and pouring it gently into a graduated cylinder by using a long neck funnel; the surface was then softly flattened with a rod, and the final volume was determined on the graduated

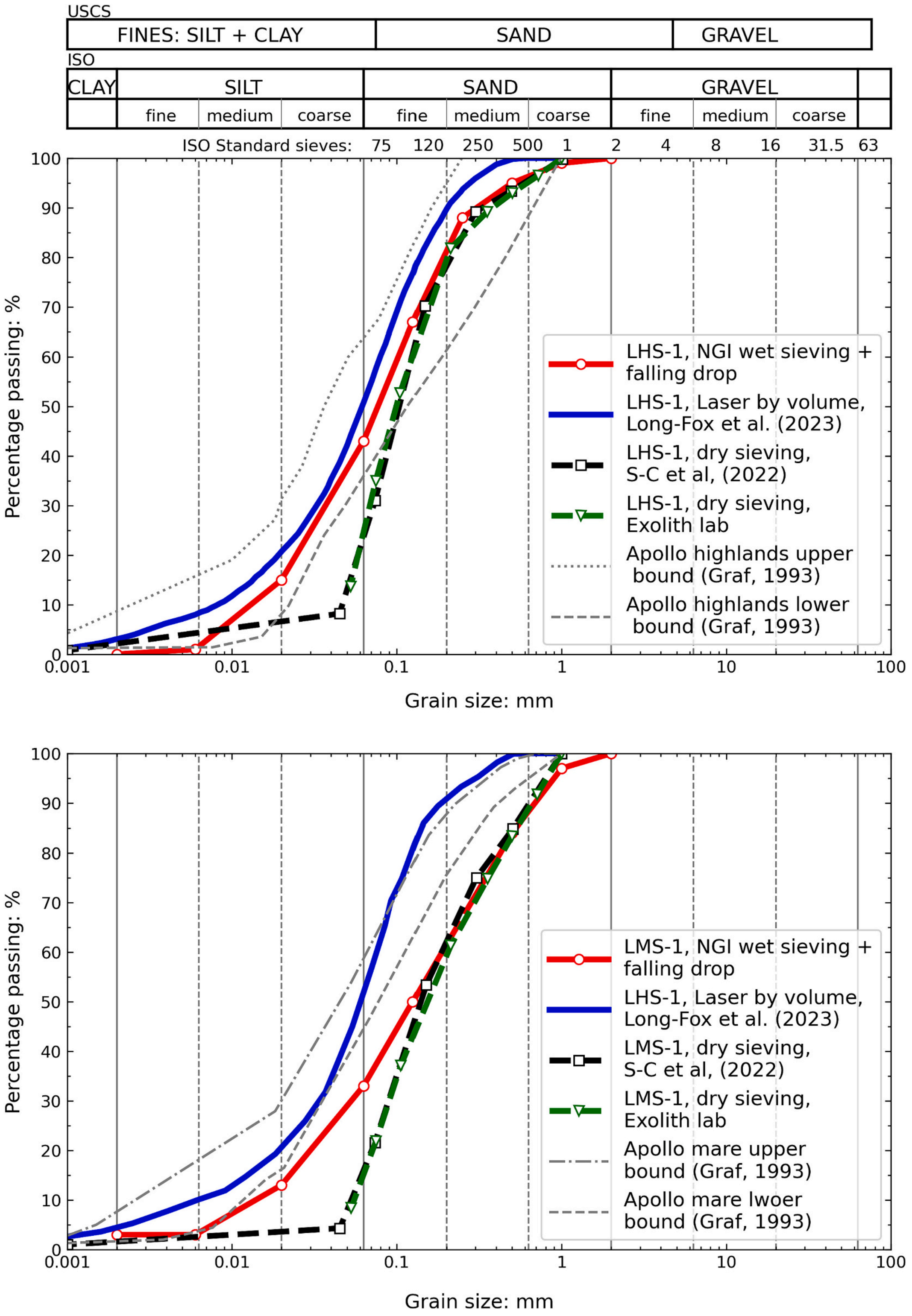

Fig. 6. Comparison of PSD curves obtained by different studies for (a) LHS-1 and (b) LMS-1.

cylinder. The mean of 10 repetitions was reported. ρ_{max} was determined by Yin et al. (2023) using 1 kg of simulant, which was poured in layers into the 1000 mL graduated cylinder gently by using the long neck funnel layer. Each layer contained about 200 g of regolith, which was tamped by a round rod until no volume change was observed. Fig. 8 also presents the lunar soil data summarized by Carrier et al. (1991) for Highlands and Mare, which were obtained over several studies using small masses of regolith (median values of 5.5 g, maximum 565 g in only one study and a minimum of 0.96 g); moreover different densification methods were used to obtain $\rho_{d,max}$ (rodding, tamping and compressing in layers, or tamping and vibration), and $\rho_{d,min}$ (placing regolith as loose as possible, or brushing it gently into a container). All mentioned studies are also listed in Table 3.

As seen in Fig. 8, there is a significant variance in the LHS-1 and LMS-1 density measurements, which we anticipated from the choice of methods used, as the same simulants were used across the different

Table 4
Comparison of LHS-1 and LMS-1 PSDs to other studies and lunar regolith.

Regolith	Study	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Sa (%)	Si (%)	C (%)	FC (%)	C_U (−)	C_C (−)	Method used
LHS-1	NGI, current study	0.013	0.035	0.102	57	43	0.3	43 (49)	0.92	7.8	Wet sieving + falling drop
	Long-Fox et al. (2023)	0.008	0.032	0.079	48	49	3	51 (58)	1.62	9.9	Laser diffraction
	Stockstill-Cahill et al. (2022)*	0.046	0.072	0.123	76	22	2	24 (32)	0.92	2.7	Dry sieving
	Exolith lab	0.055	0.090	0.203	84	16	–	15 (22)	0.73	3.7	
Apollo highlands	Upper bound (Graf, 1993)	0.002	0.019	0.050	35	56	9	64 (67)	3.61	25.0	Dry sieve + SEM
	Lower bound (Graf, 1993)	0.022	0.048	0.188	64	35	1	36 (40)	0.56	8.5	
LMS-1	NGI, current study	0.014	0.051	0.186	67	31	3	33 (38)	0.99	13.3	Wet sieving + falling drop
	Long-Fox et al. (2023)	0.006	0.033	0.075	47	49	4	52 (60)	2.42	12.5	Laser diffraction
	Stockstill-Cahill et al. (2022)	0.053	0.089	0.186	84	15	1	16 (22)	0.80	3.5	Dry sieving
	Exolith lab	N/A	0.068	0.125	74	26	–	25 (35)	N/A	N/A	
Apollo Mare	Upper bound (Graf, 1993)	0.002	0.019	0.066	41	51	8	59 (64)	2.73	33.0	Dry sieve + SEM
	Lower bound (Graf, 1993)	0.011	0.035	0.111	56	42	2	45 (49)	1.00	10.1	

* S—C = Stockstill-Cahill et al. (2022).

studies. The lunar soil data of both Highlands and Mare also shows differences, which may be attributed not only to the different methods used to determine maximum and minimum density, but also to the different PSDs. However, values obtained on LHS-1 are not necessarily comparable with the lunar soils Highlands data (especially the $\rho_{d,min}$ values which plot quite high). Additionally, for LMS-1, it is obvious that the maximum and minimum packings obtained are not comparable with the values obtained on lunar Mare regolith, and noting that given the Carrier et al. (1991) dataset was obtained on extremely small mass regolith samples using a variety of densification methods, differences should be expected. The differences between LHS-1 and LMS-1 values and lunar regolith, from the Highlands and Mare respectively, could be an indication that while we may be able to simulate lunar regolith specific gravity, or grain size, the particle shapes and intergranular voids (Carrier et al., 1991) are far from replicated. For a proper comparison of $\rho_{d,max}$ and $\rho_{d,min}$ of simulants we need to revisit the knowledge gained in the 70's, and retest lunar regolith using adequate quantities of mass and follow the most suited standard.

Comparing the data within the same regolith type in Fig. 8, for instance for LHS-1, the largest observed difference in the $\rho_{d,max}$ - $\rho_{d,min}$ value is between the method used by Long-Fox et al. (2023) and the Stockstill-Cahill et al. (2022) method, namely $\rho_{d,max,LF}$ - $\rho_{d,min,LF} = 0.59$ (1.860–1.270) and $\rho_{d,max,SC}$ - $\rho_{d,min,SC} = 0.18$ (1.56–1.38), respectively. For LMS-1, the largest differences are between the NGI method and the Stockstill-Cahill et al. (2022) method, namely $\rho_{d,max,NGI}$ - $\rho_{d,min,NGI} =$ 0.63 (2.243–1.64) and $\rho_{d,max,SC}$ - $\rho_{d,min,SC} = 0.149$ (1.730–1.580). These differences between the methods raise the following questions: (i) what are the implications of these differences, (ii) how can these differences in $\rho_{d,max}$ and $\rho_{d,min}$ be used to better classify simulants and compare to lunar regolith, and (iii) which, from all the available methods, should be used to determine $\rho_{d,max}$ and $\rho_{d,min}$ and what is the minimum regolith quantity that should be used to obtain reliable and repeatable results? Attempted answers to the first two questions are given herein, but a much larger and detailed study is needed to develop suitable and standard procedures to tackle the third question, especially if we want to study future lunar return samples.

The implications of the observed differences between the maximum and minimum dry densities mean that if we continue using a myriad of different method then values of the relative density will be unavoidably either over- or underestimated. Let us for instance calculate Dr. by assuming a fixed value of ρ_d in situ of 1.6 g/cm^3 for LHS-1 and for instance 1.7 g/cm^3 for LMS-1 (note that reported ranges of lunar Highlands are 1.4–1.8 g/cm^3 and of lunar Mare are 1.55–1.90 g/cm^3, after Carrier et al., 1991). As seen in Fig. 9a, a value of $\rho_d = 1.6$ g/cm^3 for LHS-1 leads to a Dr. ≈ 33% if the NGI-Geolabs methods is used, a value of 66% if the ASTM conformal methods by Long-Fox et al. (2023) is used and Dr. > > 100% if the Stockstill-Cahill et al. (2022) methods is used. For LMS-1 (Fig. 9b) a value of $\rho_d = 1.7$ g/cm^3 will mean Dr. = 14% by the NGI methods, Dr. = 55% using Long-Fox et al. (2023) and a staggering Dr. = 82% using the Stockstill-Cahill et al. (2022) method. Variations of relative density in the range of ±70% are observed in the above example, which is certainly unacceptable for any design of structures based on strength, stiffness, or deformation. Hence, again the emphasis is made on the need for standardization to avoid such major differences in Dr. and the reduce the potential for future design errors.

The values of $\rho_{d,max}$ and $\rho_{d,min}$ combined with ρ_s (see Table 3) for each soil can also be used to calculate e_{min} and e_{max}, respectively by Eq. (3). As seen in Fig. 10, the calculated values of e_{max} and e_{min} for lunar regolith (Highlands and Mare) seem to fit well as an upper bound in comparison to terrestrial soils. Based on the limited data, obtained on small quantities of lunar regolith (compiled by Carrier et al., 1991), an empirical regression is proposed herein for lunar soils:

$$e_{max} = 0.312 \bullet e_{max} - 0.502. \tag{4}$$

The above regression can be useful approximation if the method used to determine e_{max} and e_{min} is adequate, provided that the methods used are similar to those used in the late 60's (and that those previously used methods are rigorous and repeatable). Moreover, provided that the method used to determine e_{max} and e_{min} is suitable and comparable with the Carrier et al. (1991) database, Fig. 10 can also be used to assess if a regolith simulant fits within the lunar soil e_{max} and e_{min}. The observation here is that all the values of e_{max} and e_{min} obtained in this study of LHS-1 and LMS-1 regolith simulant fit within the values for 'sands with fines' and 'sands with clay' proposed by Cubrinovski and Ishihara (2002), based on a database of terrestrial soils; this indicates that those LHS-1 and LMS-1 simulants do not necessarily capture all features of lunar regolith. Note also from Fig. 10 that the e_{max} and e_{min} database of Stockstill-Cahill et al. (2022), on different regolith simulants, plot below general trends of terrestrial soils.

6. Summary and conclusions

A laboratory geotechnical investigation into two lunar regolith simulants has been completed. A comparison to other results from the literature has been presented, and the following conclusions may be drawn from this comparative study.

- Even though the particle size distributions of lunar regolith are replicated by the LHS-1 and LMS-1 simulants, particle shapes (calculated from a 2D-image analysis) are not. For instance, the aspect ratio and roundness of both simulants are higher than those reported for lunar regolith. This is an important observation, given

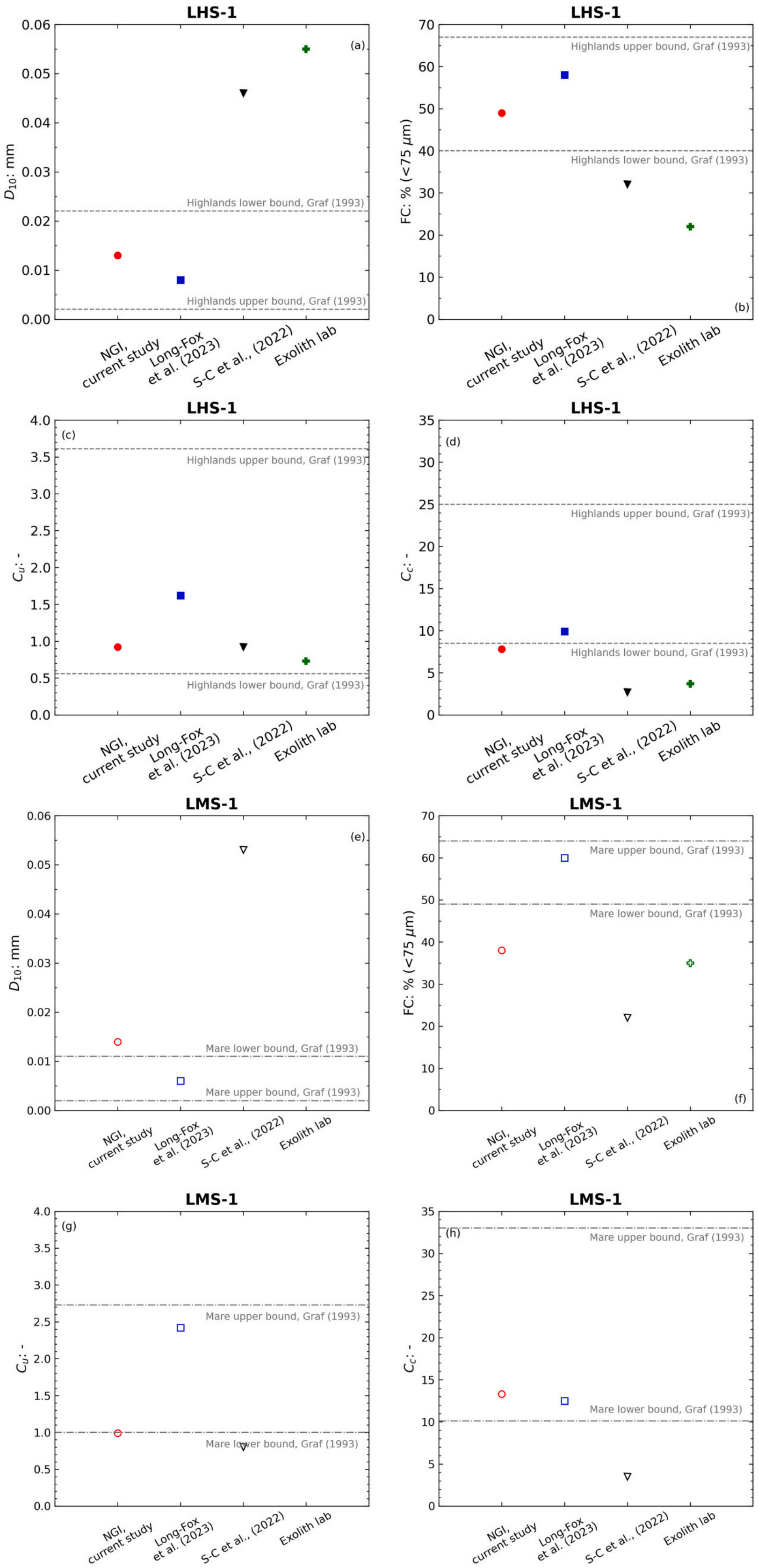

Fig. 7. Comparison of different studies on LHS-1, LMS-1 and lunar soil: D_{10} (a) and (e), FC (b) and (f), C_c (c) and (f), and C_u (d) and (g).

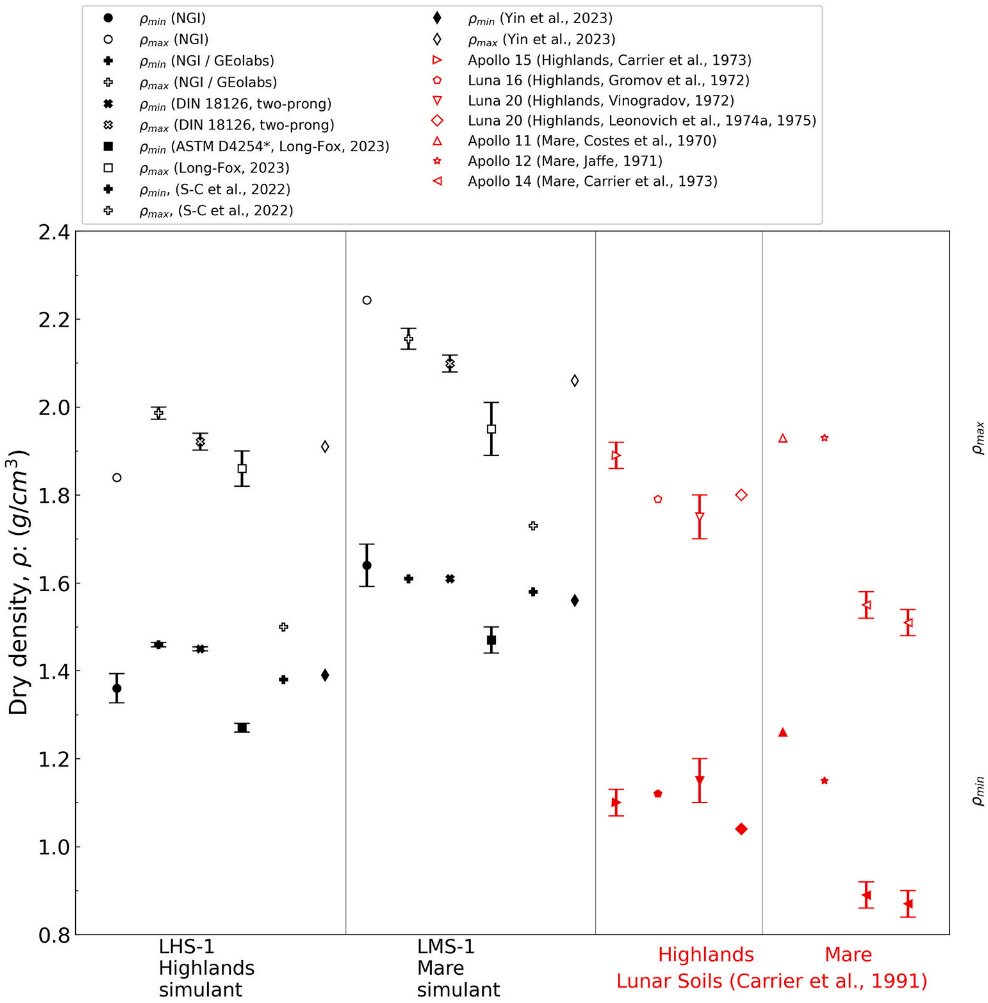

Fig. 8. Minimum (closed symbols) and maximum (open symbols) dry densities of the LHS-1 and LMS-1 simulants (black) obtained by different methods compared to measurements on lunar regolith (red) from the literature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that particle morphology and the intergranular porosity directly control the density of regolith.

- The grain density (or specific gravity) of LHS-1 is lower than the average for lunar regolith, while LMS-1 fits within the lunar range. The values of grain density of LHS-1 are not consistent between laboratories, even though the same methods were used across laboratories.
- A significant method dependency is observed in particle distribution curves. A comparison between wet pluviation and falling drop, laser diffraction and dry sieving shows that derived value of fines content, D_{10}, and PSD characteristics vary significantly from method to method. If new regolith studies are to capture the PSD of lunar regolith, modern methods should be used to reanalyse Apollo return samples.
- An extreme method dependency is observed in the determination of limiting packing values (maximum and minimum dry densities). The use of different methods leads to significant variations in estimating the relative density of specimens. This can be problematic when relative density is used later for advanced testing, from which strength and stiffness are derived.
- The differences between the $\rho_{d,max}$ and $\rho_{d,min}$ values of the lunar regolith and the values obtained for the LHS-1 and LMS-1 simulants may be an indication of the simulants inability to replicate the complex particle shapes of lunar regolith. This deserves further investigation.
- Using the e_{min} and e_{max} data available in the literature, a relationship between those values is suggested, which can be used as a proxy to assess if a simulant captures the lunar regolith particle’s morphological characteristics. Nonetheless, we should be careful when using literature results from the 60’s and 70’s as the amount of regolith (mass) used to obtain the limiting void ratios was extremely low.
- Finally, the e_{min} and e_{max} results for LHS-1 and LMS-1 simulants using 6 different methods are lower than the expected lunar regolith values and fit more within values for sands with fines on earth.

The study presented herein highlights the method dependency of geotechnical index test performed on two lunar regolith simulants. This study is an appeal for standardization and for a community agreement to introduce best practices among the simulant research community. The use of non-standardized methods can lead to significant errors in the estimation of engineering parameters and later to failure in foundation design, infrastructure settlements, capacity issues, thermal properties, etc., on subsequent lunar missions. A worldwide standardization of geotechnical tests would allow researchers and engineers to create systematic datasets that capture clearly and consistently the mechanical behaviour of regolith. The safety and success of future missions and investigations of celestial bodies depends on our ability to predict the behaviour of surficial regolith; hence, well-documented testing specifications that represent the state-of-the-art and -practice in the form of regulations and guidelines are paramount.

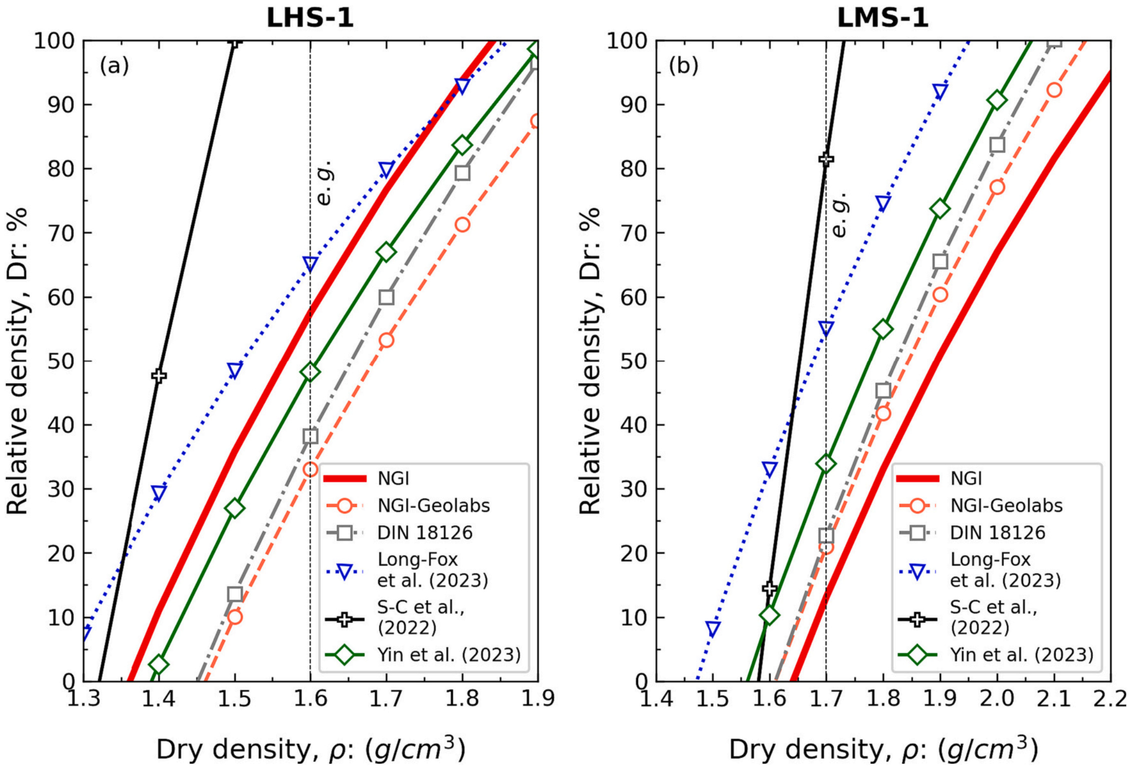

Fig. 9. Effect of varying $\rho_{d,max}$ $\rho_{d,max}$ and $\rho_{d,min}$ on the relative density of LHS-1 and LMS-1. See text for details.

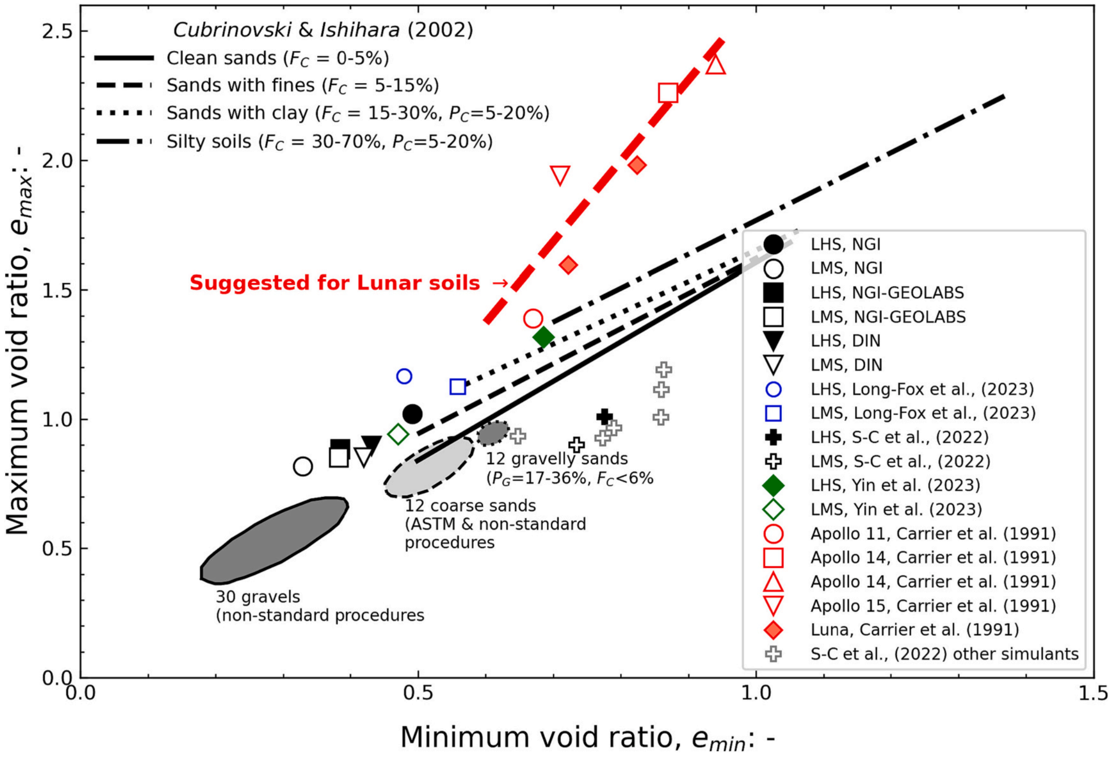

Fig. 10. e_{min} vs. e_{max} of lunar regolith and simulants compared to terrestrial soils.

Declaration of Competing Interest

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

Data availability

All data or code generated during this study is available upon request.

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References

ASTM, 1999. Test Method for Relative Density of Cohesionless Soils. ASTM standard D-2049. ASTM International, West Conshohocken, PA.

ASTM, 2016a. Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM standard D854 – 14. ASTM International, West Conshohocken, PA.

ASTM, 2016b. Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density. ASTM standard D4254:2016. ASTM International, West Conshohocken, PA.

ASTM, 2016c. Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table. ASTM standard D4253–16. ASTM International, ASTM International, West Conshohocken, PA.

ASTM, 2017a. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM Standard D2487 – 17. ASTM International, West Conshohocken, PA.

ASTM, 2017b. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM standard D4318: 2017. ASTM International, West Conshohocken, PA.

ASTM, 2018. Standard Test Method for Measurement of Soil Resistivity Using the Two-Electrode Soil Box Method. ASTM standard G187: 2018. ASTM International, West Conshohocken, PA.

ASTM, 2022. Standard Test Method for Determination of Thermal Conductivity of Soil and Rock by Thermal Needle Probe Procedure. ASTM standard D5334: 2022. ASTM International, West Conshohocken, PA.

Budhu, 2010. Soil Mechanics and Foundations, 3rd edition. John Wiley & Sons, Inc, p. 780. ISBN: 978-0-470-55684-9.

Butler, J.C., King, E.A., 1974. Analysis of the grain size-frequency distribution of lunar fines. In: Proceedings of the Fifth Lunar Conference, vol. 1, pp. 829–841.

Carrier, W.D., Olhoeft, G.R., Mendell, W., 1991. Chapter 9: Physical properties of the lunar surface. In: The Lunar Sourcebook. Cambridge University Press.

Collins, P.J., Edmunson, J., Fiske, M., Radlinska, A., 2022. Materials characterization of various lunar regolith simulants for use in geopolymer lunar concrete. Adv. Space Res. 69 (11), 3941–3951.

Cubrinovski, M., Ishihara, K., 2002. Maximum and minimum void ratio characteristics of sands. Soils Found. 42, 65–78.

DGF, 2001. Klassifikationsforsøg - Relativ lejringstæthed. In: Laboratoriehåndbogen. DGF Bulletin 15. Dansk Geoteknisk Forening.

DIN, 1996. Bestimmung der Dichte nichtbindiger Böden bei lockerster und dichtester Lagerung. In: DIN 18126: 1996–11 Deutsches Institut für Normung, Berlin, Germany.

Duri, L.G., Caporale, A.G., Rouphael, Y., Vingiani, S., Palladino, M., De Pascale, S., Adamo, P., 2022. The potential for lunar and Martian regolith simulants to sustain plant growth: a multidisciplinary overview. Front. Astron. Space Sci. 8 https://doi.org/10.3389/fspas.2021.747821.

Easter, P., Long-Fox, Z., Landsman, J., Metke, A., Britt, D., 2022. Comparing the effects of mineralogy and particle size distribution on the angle of repose for lunar regolith simulants. In: 53rd Lunar and Planetary Science Conference. Houston, Texas. April 2022. https://www.hou.usra.edu/meetings/lpsc2022/pdf/1980.pdf.

Engelschiøn, V.S., Eriksson, S.R., Cowley, A., Fateri, M., Meurisse, A., Sperl, M., Kueppers, U., 2020. EAC-1A: a novel large-volume lunar regolith simulant. Sci. Rep. 10, 5473. https://doi.org/10.1038/s41598-020-62312-4.

Graf, J.C., 1993. Lunar Soils Grain Size Catalog. NASA Reference. Publication 1265.

ISO, 2002. Geotechnical Investigation and Testing - Identification and Classification of Soil - Part 1: Identification and Description. ISO standard 14688–1:2002. International Organisation for Standardization (ISO).

ISO, 2015. Geotechnical Investigation and Testing – Laboratory Testing of Soil – Part 3: Determination of Particle Density. ISO standard 17892–3: 2015. International Organization for Standardization, Geneva, Switzerland.

ISO, 2018a. Geotechnical Investigation and Testing – Laboratory Testing of Soil – Part 4: Limiting Materials - Determination of Size Distribution by Dry and Wet Sieving. ISO standard 20977: 2018. International Organization for Standardization, Geneva, Switzerland.

ISO, 2018b. Geotechnical Investigation and Testing — Laboratory Testing of Soil — Part 12: Determination of Liquid And Plastic Limits. ISO standard 17892–12: 2018. International Organization for Standardization, Geneva, Switzerland.

Knudsen, S., Powell, J.M., Lunne, T., Thomsen, N.V., Krogh, L., Barwise, A., 2020. Development of new robust procedures for the determination of maximum and minimum dry densities of sand. 4th International Symposium on Frontiers in Offshore Geotechnics. In: Proceedings. (ISFOG). Austin Texas, Aug. 28–31 2022, pp. 1046–1055.

Krumbein, W.C., Sloss, L.L., 1963. Stratigraphy and Sedimentation (No. QE571 K7 1963). Freeman and Company, San Francisco.

Langseth, M.G., et al., 1972. Heat-flow experiment. In: Apollo 15 Preliminary Science Report (Chapter 11).

Langseth, M.G., Keihm, S.J., Chute, J.L., 1973. Heat-flow experiment. In: Apollo 17 Preliminary Science Report (Chapter 9).

Long-Fox, J.M., Landsman, Z.A., Easter, P.B., Millwater, C.A., Britt, D.T., 2023. Geomechanical properties of lunar regolith simulants LHS-1 and LMS-1. Adv. Space Res. https://doi.org/10.1016/j.asr.2023.02.034.

Lunne, T., Knudsen, S., Blaker, Ø., Vestgarden, T., Powell, J., Wallace, C., Krogh, L., Thomsen, N., Yetgenir, G., Ghanekar, R., 2019. Methods used to determine maximum and minimum dry unit weight of sand. Is there a need for a new standard? Can. Geotech. J. 56 (4), 536–553.

McKay, D.S., Fruland, R.M., Heiken, G.H., 1974. Grain size and the evolution of lunar soils. In: Proceedings of the Fifth Lunar Conference, 1, pp. 887–906.

Moum, J., 1965. Falling drop used for grain size analysis of fine grained materials. In: Sedimentology, vol. 5. Norwegian Geotechnical Institute. Publication, pp. 343–347. No. 4. 70, 1966.

Santamarina, J.C., Cho, G.C., 2004. Soil behavior: The role of particle shape. In: Proc. Skempton Conf., March, London.

Smits, K.M., Sakaki, T., Limsuwat, A., Illangasekare, T.H., 2010. Thermal conductivity of sands under varying moisture and porosity in drainage-wetting cycles. Vadose Zone J. 9 (1) https://doi.org/10.2136/vzj2009.0095.

Stockstill-Cahill, K.K., Martin, A., Wagoner, C., 2022. JHU-APL LSII report: 2022 Lunar simulant assessment. Johns Hopkins Applied Physics Laboratory, p. 60.

Xiao, X., Yu, S., Huang, J., Zhang, H., Zhang, Y., Xiao, L., 2022. Thermophysical properties of the regolith on the lunar far side revealed by the *in situ* temperature probing of the Chang'E-4 mission. Natl. Sci. Rev. 9 (11) https://doi.org/10.1093/nsr/nwac175.

Yin, K., Cheng, Z., Liu, J., Chen, A., 2023. Shear properties of LHS-1 and LMS-1 lunar regolith simulants. Planet. Space Sci. 226, 105630.

Zheng, J., Hryciw, R.D., 2015. Traditional soil particle sphericity, roundness and surface roughness by computational geometry. Géotechnique 65 (6), 494–506. Script: https://github.com/geosharma/sphericity_and_roundness.