



Assessment of geotechnical properties of lunar soil simulant's for lunar missions

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Prototype-based experimental studies at the simulated environmental conditions are essential for the planned Chandrayaan missions of the Indian Space Research Organization (ISRO). A large quantity of lunar simulants was needed to prepare the lunar surface testbed, which cost more expensive to import. Therefore, the ISRO has intended to develop an indigenous new lunar simulant. All the available lunar soil simulants have been developed to mimic the actual lunar soil properties. Likewise, the new lunar soil simulant should mimic the properties of actual lunar soil. Hence, it is essential to examine the fidelity and properties of the existing lunar simulants with the actual lunar soil. This paper reviews the chemical composition, mineralogy, geotechnical and geomechanical properties of the past developed lunar simulants (mare and highland simulants) with actual lunar soils. Also, the review has provided an increased understanding of previous research on lunar soil development methods and materials used. Both mare and highland simulants discussed have variations with actual lunar soil; because the lunar simulants have been tested in the terrestrial environment, which can have significant effects on results. The variations between terrestrial simulants and lunar regolith and the related engineering implications are discussed.

Keywords: Chandrayaan mission, Bulk density, Shear strength, Trafficability, Bearing capacity

1 Introduction

Understanding the geotechnical properties of the lunar soil was highly imperative for the design of rovers, landers, wheel-soil interaction studies, and successful execution of the lunar mission¹⁻⁵. Also, the in-situ resource utilization (ISRU) related studies for futuristic lunar habitation are entirely dependent on the chemical composition, geotechnical properties of the lunar soils⁶⁻¹⁰. The complete research about the lunar soil/regolith was impossible using the limited amount of lunar returned lunar soil samples.

Also, the significance of the lunar soil leads to developing lunar simulants to possess the actual lunar soil properties using terrestrial materials. In the initial stage during the Apollo era, the developed simulants have relatively low fidelity due to the lack of lunar regolith samples¹¹. After the successive Apollo missions, National Aeronautics and Space Administration (NASA), Alabama, Washington DC has narrated the possible development guidelines for lunar simulants, which includes the actual lunar soil properties^{12,13}, materials resources¹⁴, and development techniques¹⁵, etc. Also, many researchers and space research organizations have done extensive research on

the development of lunar simulants to represent the similar properties of the actual lunar soils using various terrestrial materials such as rocks (basalt & anorthosite)¹⁶⁻¹⁸, volcanic ashes¹⁹⁻²², minerals, and soils²³, etc.,. The simulants have been developed and used for various lunar related studies and R&D works of different space research organizations.

Indian Space Research Organization (ISRO) has planned the Chandrayaan missions (II & III) to explore the South Polar Region of the Moon and for possible Moon colonization in the future. To carry out the experimental studies, such as the design of lander and rovers, the soft landing of the lander under the simulated lunar environmental conditions, and other related R&D work, the ISRO has intended to develop a new lunar simulant. In order to gain the basics for developing new simulants, it is essential to review the properties such as chemical composition, mineralogy, geotechnical and geomechanical behavior of the actual lunar soils, and past developed lunar soil simulants. Various space research organizations have developed many lunar soil simulants in different countries in the past decade. The lunar simulants have been produced in two different types named mare region soil simulants (JSC-1, JSC-1A, MLS-1, GRC-1,

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KLS-1, BP-1, TJ-1) and highland region soil simulants (OB-1, NAO-1, NU-LHT-1M/2M), which are the two major regions of the lunar surface. The development of simulants is based on the properties and location of the reference lunar soils collected from the lunar surface. Even though the simulants have been developed to represent the lunar soil, the terrestrial materials property will not wholly mimic the features of the lunar regolith. Hence, the variation in the physical and engineering properties of the terrestrial simulants has to be considered for discussions and revealed for future improvements in the development of new lunar simulants.

In this study, the mare soil simulants (JSC-1, BP-1, KLS-1, & DNA-1A) and highland soil simulants (NAO-1, NU-LHT-2M) were reviewed with the actual lunar soil properties. McKay *et al.*¹⁹ have developed the Johnson Space Centre simulant (JSC-1) using the basaltic volcanic ash deposit. In the initial stage, the JSC-1 has been widely used for extensive research on vehicle mobility and ISRU related studies²¹. Recently the simulant BP-1 has developed using the black point basalt flow and washing paste collected from the volcanic ash field²¹. The Korean lunar simulant KLS-1 was developed to match the iron content of the lunar soil by using natural basalt¹⁶. The DNA-1A was developed by Marzulli and Cafero²² using the cinder quarry ash to represent the mare soils. The lunar highland simulant NU-LHT-2M has been developed to match the properties of the highland soil by Zeng *et al.*¹⁷. NU-LHT has been made from Stillwater Norite, Anorthosite, Hartzburgite, and Twin Sisters Dunite. National Astronomical Observatories (NAO), the Chinese Academy of Sciences, has developed a simulant NAO-1 using the anorthosite rocks and fired glasses to resemble the highland soils¹⁸.

2 Materials and Methods

2.1 Lunar soil

The lunar surface was broadly divided into two major regions, such as the mare region, which consists of basaltic rock particles, and the highland region, which consists of anorthosite rock particles. The lunar soil is a mechanically disintegrated particle from basaltic and anorthositic rocks. Individual lunar soil particles are mostly glass bonded aggregates (agglutinates), as well as various rock and mineral fragments¹³. The elements found at Earth, such as Si, O, Al, Mg, Ca, and Mg, together with lesser elements such as Na, K, and S, are also found on the Moon.

Oxygen is still the most abundant major element, at about 45% (by weight). Silicon is still second, at 21%. Aluminum is third at about 13% for the highlands, although only about 5% for the mare region¹³. Calcium is next, at about 10% for the highlands and 8% for the mare region. Iron contributes about 6% to the highlands but 15% to the mare region¹³. Magnesium comes next at 5.5% for both types of material. Titanium and Na each contribute a fraction of a percent in the highlands, but the average Ti concentration exceeds 1% and may be as high as ~5% in the mare region¹³. In general, the elements discussed above are found in the form of oxides such as SiO₂, Al₂O₃, CaO, TiO₂, FeO, Fe₂O₃, MgO, MnO, Na₂O, K₂O, etc. in both the regions of the Moon²⁴⁻²⁶.

Concerning the presence of minerals, the rocks found on the lunar surface contain plagioclase feldspar (consists of high concentration Al) at a greater proportion at highlands (anorthosite rocks) than that in the mare region (basaltic rocks). The highland region anorthosite rocks consist of greater than 90% plagioclase, norite (roughly equal proportions of plagioclase and low-Ca pyroxene), and troctolite (plagioclase and lesser amounts of olivine)^{13,27}. In contrast to the lunar highland rocks, the mare basalts consist of high proportion high-Ca and low Mg type pyroxene, lower proportion plagioclase, and low Mg type olivines. The presence of pyroxene and olivine proportions was more in the mare region than in the highlands. The mare basaltic lunar soil has a high concentration of Fe, and Ti (oxides of FeO and TiO₂), which is found low in the anorthosite derived particles in highlands^{13,24,25}.

2.2 Simulants

Most of the lunar soil simulants (mare and highland) are intended to represent the similar chemical composition and mineralogy of the respective lunar soils collected from the lunar surface. The appropriate terrestrial materials (rocks, volcanic ash, minerals, etc.) are found and subjected to various mechanical processes such as grinding, milling, and sieving, etc., to make fine grains or required particle sizes to match the gradation of the actual lunar soils. Before the mechanical process, the materials matching the chemical composition and mineralogy with the respective lunar soils (mare and highland soils) were found and then subjected to the above process. The comparison of major oxides such as SiO₂, Al₂O₃, CaO, TiO₂, FeO, Fe₂O₃, MgO, and Na₂O of both mare (JSC-1, BP-1, KLS-1 & DNA-

1A)^{16,19,21,22} and highland simulants (NU-LHT-2M & NAO-1)^{17,18} with their respective lunar soils (mare or highland soils) was presented in the Figs 1 and 2. In general, the presence of FeO is more than the Fe₂O₃ in lunar soils (mare and highland soils) because the lunar soils were less oxidized than the terrain soils. So, the presence of FeO and Fe₂O₃ would be encountered in the root materials (terrain soils, rock, ashes, and minerals, etc.)¹⁵ of the simulants. Therefore, the oxides FeO and Fe₂O₃ were found in both mare and highland simulants. Hence, the FeO and Fe₂O₃ were considered as a base, and the percentage presence of the other oxides was discussed.

Fig. 1(a) is showing the distribution of major oxides such as SiO₂, Al₂O₃, and CaO with respect to FeO. It is observed that the mare soils (collected during Apollo 11 to 15, 17 and Luna 16 and 24) are having almost a similar percentage of FeO (15 - 17%), SiO₂ (40 - 48%), Al₂O₃ (12 - 17%), and CaO (10 - 13%). The percentage of minor oxides (MgO, TiO₂& Na₂O) presence in the mare soils is showing (Fig. 1(b)) a slightly scattered and comparatively similar percentage of oxides with respect to FeO. But when comparing the major and minor oxides present in the mare soil simulants, Figs. 1(a & b) are showing a similar percentage presence of SiO₂, Al₂O₃, CaO, MgO, TiO₂, and Na₂O

with the mare soils. But the percentage of FeO was not matching with the mare soil percentage. When the oxides FeO and Fe₂O₃ were added together is having a similar acceptable percentage of Fe (FeO + Fe₂O₃) (Figs. 1(c & d)) with the mare soils. The highland soils and simulants (Fig. 2(a & b)) show that the SiO₂, Al₂O₃, CaO, MgO, TiO₂, and Na₂O percentages were similar. Comparing the FeO concentration, the simulants have a quiet variation with the highland soils, and when adding Fe₂O₃ percentage with FeO, the percentage was comparatively matching to each other. Also, it is cleared that the Fe (as FeO) concentration of the highland soils and simulants is lesser than the mare soils and simulants, which is discussed above. Overall, the major (except FeO) and minor oxide composition of both lunar simulants are similar to their respective lunar soils. Also, the presence of Fe₂O₃ was encountered at a lower percentage. It is understood that the basalt rocks and basaltic flow volcanic ashes are well suitable for the development of mare soil simulants, whereas anorthosite rocks for highland soil simulants. Also, the addition of some foreign minerals will support the simulants to match the chemical composition and mineralogy of the respective lunar soils. The chemical composition of the simulants will not play a crucial role in the design of the lander, rover,

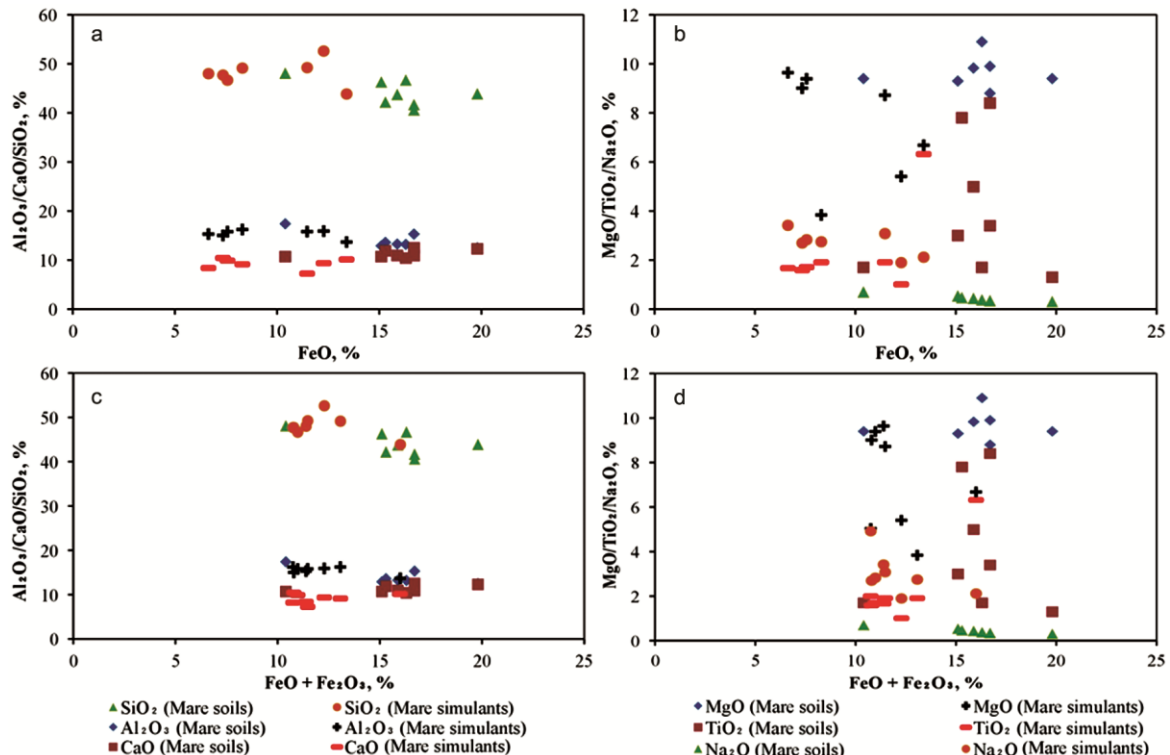


Fig. 1(a and b) — Comparison of major and minor oxides composition of mare soils and simulants respect to FeO, (c and d) - comparison of major and minor oxides composition of mare soils and simulants respect to FeO + Fe₂O₃.

and wheel-soil interaction studies rather than ISRU related studies. Therefore, it is essential to review the geotechnical properties of the lunar simulants.

3 Results and Discussion

3.1 Geotechnical properties

The geotechnical properties of the lunar soil tend to fall in a fairly narrow range because of the variation in the lunar environmental conditions and geology of the lunar terrain. As discussed, the mineralogy, particle size, particle shape, absence of water, and clay minerals or organic materials on the lunar surface differentiated the properties of the lunar soil as unique as the soil on the Earth¹³. The geotechnical properties were determined as per the procedure prescribed in ASTM standards. The variation in geotechnical properties of the lunar mare soil simulants (JSC-1, BP-1, KLS-1, and DNA-1A) and highland soil simulants (NU-LHT-2M and NAO-1) with the lunar soil were discussed.

3.1.1 Particle size distribution

The particle size distribution is a variable that controls the strength and compressibility of the lunar soil²⁸⁻³². The particle size (lesser than 75 microns) has significantly influenced geotechnical/ geomechanical properties due to inter-particle forces at the micro-

level^{28,30,32}. It is also mentioned that the particle size distribution was evaluated to be one of the highest-ranked factors³³ for simulants to be representative of the actual properties of lunar soils. In both mare and highland regions, the lunar soil had particle sizes lesser than 1 mm (40 to 65 percent fines) with boulders (in some areas)^{12,13,28,29}. Meteorite impact on the lunar surface produces a consistent, broadly graded soil. The soils are described as brownish to medium gray, slightly cohesive granular soil in the silt to fine sand range^{13,29}. The soils are well graded, with a wide range of particle sizes. The principal method of determining the particle size distribution of unconsolidated material is sieving, which is generally effective for particle sizes greater than about 10 μm. As is well known, geotechnical engineers plot cumulative particle size distribution as percent passing versus logarithm base 10 of the particle size in millimeters (i.e., on semi log graph paper), whereas geologists plot percent retained versus logarithm base 2 of the particle size in millimeters. Depending on the geologist, the percent retained axis is either plotted on an arithmetic scale or a probability scale²⁹.

Geotechnical engineers only distinguish between well-graded and poorly graded sands [ASTM D 2487 (1994)], or [Unified Soil Classification System

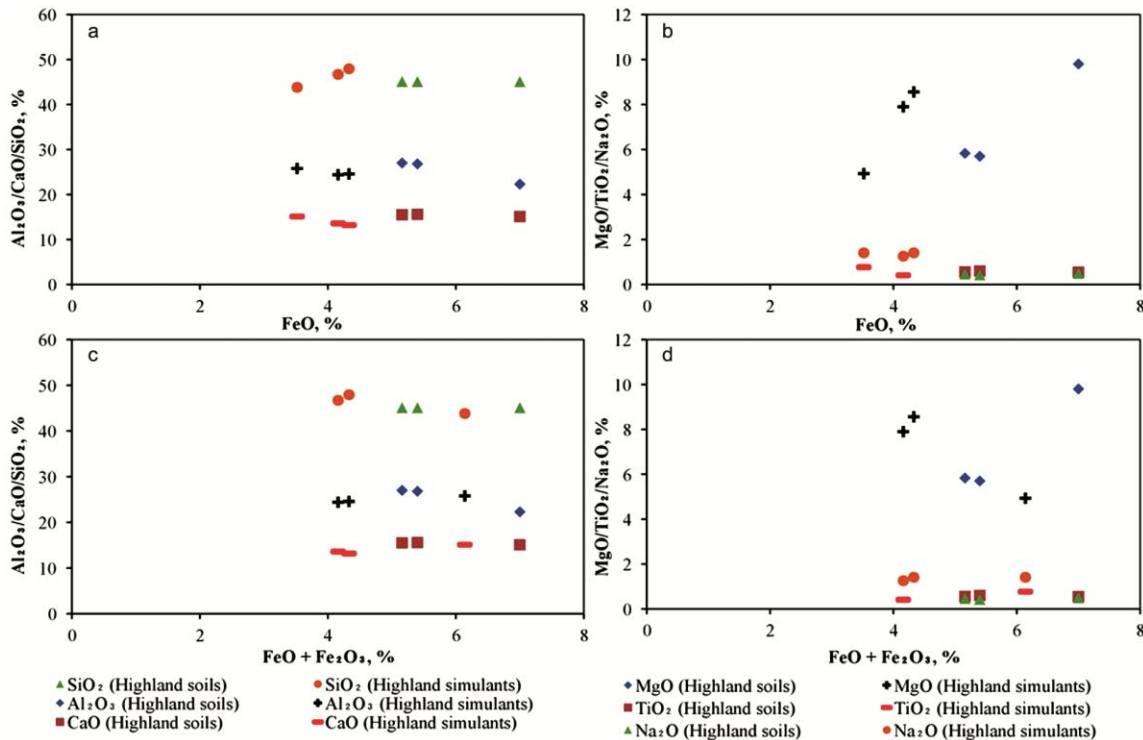


Fig. 2(a & b) — Comparison of major and minor oxides composition of highland soils and simulants respect to FeO, (c & d) comparison of major and minor oxides composition of highland soils and simulants respect to FeO + Fe₂O₃.

(USCS)]^{16,17,18,29}. This determination is based on the coefficient of uniformity, C_u , and the coefficient of curvature, C_c . The C_u (Eq. 1) and C_c (Eq. 2) values are calculated by using the formulas given as,

$$C_u = \frac{D_{60}}{D_{10}} \quad \dots (1)$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \quad \dots (2)$$

where, D_{60} , D_{30} , and D_{10} refer to particle-size diameters corresponding to 60, 30, and 10% passing, respectively. As is well known, if sand contains less than 12% fines and if C_u is >6 and $1 < C_c < 3$, then it is classified as well graded. If C_u , 6 or C_c , 1 or C_c , 3, then it is classified as poorly graded^{17,18,20,21}. In geological terms, the distribution may be characterized by parameters such as mean particle size, median particle size, sorting, skewness, and kurtosis, which are standard statistical measures for any grouped population. The below-given equations 3 to 7 will be used to calculate the parameters²⁹.

$$\text{Median} : \phi_{Md} = \quad \dots (3)$$

$$\text{Mean} : \phi_{Mn} = (\phi_{16} + \phi_{50} + \phi_{84})/3 \quad \dots (4)$$

Sorting :

$$\sigma_s = [(\phi_{84} - \phi_{16})/4] + [(\phi_{95} - \phi_5)/6.6] \quad \dots (5)$$

Skewness:

$$S_k = \left(\frac{\phi_{95} + \phi_5 - 2\phi_{50}}{2(\phi_{95} - \phi_5)} \right) + \left(\frac{\phi_{84} + \phi_{16} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} \right) \quad \dots (6)$$

$$\text{Kurtosis} : K_r = \frac{\phi_{95} - \phi_5}{2.44(\phi_{75} - \phi_{25})} \quad \dots (7)$$

Sorting, σ_s , is essentially the standard deviation of the particle size distribution, and it represents the overall inverse slope of the curve on probability graph paper: A vertical line (sorting = 0) would imply a uniform particle size; a horizontal line (sorting = ∞) would imply an unbounded range of particle size. Skewness measures the asymmetry of the size distribution. The value 0 denotes the symmetrical distribution of soil, and +0.1 to -0.1 describes the nearly symmetrical distribution. Also, Positive skewness implies excess fine material; negative skewness implies excess coarse material.

Kurtosis measures the "peakedness" of a particle size distribution if it were plotted as a Gaussian "bell" curve. For normal curves, $K_r = 1$; the mathematical limits are + 0.41 to infinity, although values beyond 5.0 are rare. A value of K_r greater than 1 implies that the center portion of the distribution is better sorted than the tails, and the bell curve is excessively peaked (or leptokurtic)²⁹. A value less than 1 implies the tails of the distribution are better sorted than the center portion, and the bell curve is flat peaked (or platykurtic). Strongly platykurtic distributions can be bimodal. According to the geotechnical system, lunar soil is classified as sandy silt/silty sand, wellgraded^{12,13,29}. The measured C_u and C_c values of the lunar soil are ranged from 12-16 and 1-2.8. According to the geologic system, lunar soil is classified as very fine sand, very poorly sorted, nearly symmetrical, and mesokurtic²⁹. The results of sieve analysis show that the upper and lower particle size

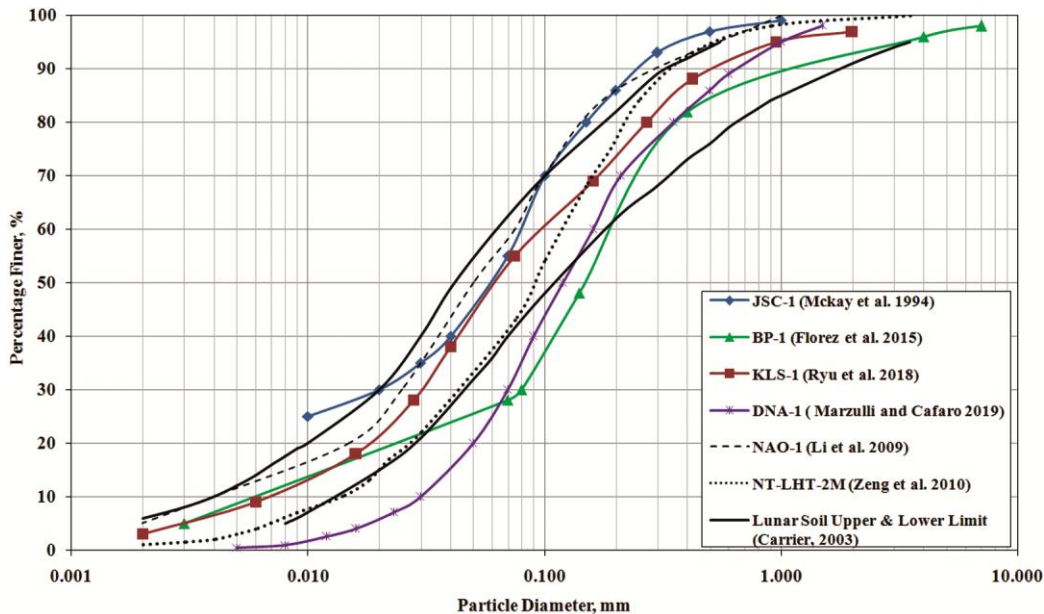


Fig. 3 — Comparison of the grain-size distribution curve of lunar soil and simulants

distribution limits of the lunar soil with simulants in Fig. 3.

From Fig. 3, it is observed that the mare soil simulants KLS-1 is having a maximum similarity in gradation than the other lunar simulants (JSC-1, BP-1 & DNA-1A) with lunar soils. Both highland simulants (NU-LHT-2M and NAO-1) are having better particle size distribution with the lunar soils. The simulants (KLS-1, NU-LHT-2M & NAO-1), which have better gradation with the lunar soils, have well-mixed different sizes of pulverized rock (basalt or anorthosite) particles¹⁶⁻¹⁸. Often the simulants developed with volcanic ashes and other silt particles (rocks, quarry dust) are having slight variation with the lunar soil's particle size distribution. The simulants having better gradation will emulate better geotechnical properties of the lunar soils. Also, it is observed that the uniformity coefficient of all the mare soil simulants, including NU-LHT-2M, is lesser than the value of the lunar soil ($C_u = 16$)²¹. It denotes that the simulants except NAO-1 are more prone to reach loose states under self-weight compaction and also result in different soil porosity during compaction.

3.1.2 Particle morphology

Particle shape and angularity are also important properties that directly affect strength in granular materials. The shape of the particles is defined using various shape parameters such as elongation, aspect ratio, and roundness. Elongation is defined as the ratio of the major to intermediate axes of the particle or length to width. The measured elongation of the lunar soil ranged from 1.31-1.39¹³. In geotechnical studies, the aspect ratio is inversely related to elongation; it is defined as the minor axis ratio to the major axis of an ellipse fitted to the particle by a least-squares approximation. The elongation of the lunar soil particles was slight to moderately elongated, with elongation values of 0.4 to 0.7¹³. The ratio of the average of the radii of the corners of the particle image to the radius of the maximum inscribed circle is defined as roundness. The measured roundness values of the angular and subangular particles ranged from 0.19-0.26 and 0.20-0.25¹³.

Liu *et al.*^{34,35} identified and narrated five different types of particle shapes: glass beads, vesicular texture, angular shards, blocky fragments, and aggregated particles in lunar soils. In general, the geometrical shapes of the glass beads vary from perfect round spheres to elongated ellipsoids, dumbbells, and teardrops as the centrifugal forces increase³⁷. The

vesicular texture grains contain the different sizes ($0.1\mu - 4\mu$ in diameter) of vesicles formed during the melting of lunar soil particles on meteoroid impacts. Angular shards are typically broken glasses with sharp edges as a result of the crushing of larger glassy fragments. The particles, which have sharp, irregular edges, fall under blocky fragments, and such particles in lunar soils are in the distinct minority. Aggregated particles are found in the uncleaned samples because the small particles are loosely attached to each other or to the surfaces of the large particles. Furthermore, due to the elongation, the particles tend to pack together with a preferred orientation of the long axes. This effect has been observed in lunar core tube samples and laboratory simulations, and the orientation has been found to be dependent on the mode of deposition¹³. Because of this preferred particle orientation, the physical properties of the lunar soil in situ are expected to be anisotropic. Also, many of the particles are not compact but have irregular, often reentrant surfaces. These particle surface irregularities especially affect the compressibility and shear strength of the soil¹³.

The simulants developed using volcanic ashes formed from the molten and cooled magmas mostly have a vesicular texture with smaller and larger cavities^{19,21,22,34}. The same has been observed in the JSC-1, BP-1, and DNA-1A particles¹⁹⁻²², which are developed with basaltic flow volcanic ashes. BP-1 particles also fall under the type of aggregated particles because of the attached smaller particles on the surface of the larger particles. KLS-1, NU-LHT-2M, and NAO-1 particles^{16,17,18} are falling under the type of blocky fragments since the particles have sharp edges, broken minerals, and non-vesicular texture^{17,18,34} because of having pulverized basalt and anorthosite rock particles^{34,38}. It is noted that the highland simulants are often developed using the pulverized terrestrial anorthosite rocks, and these particles are not matching with the morphology of the lunar soils and most of the mare soil simulants, which are representing similar morphology of the lunar soils. The shape of the particles should be considered one factor for the development of simulants representing any lunar soils since it influences the compaction, stiffness, and strength properties of the lunar soil.

3.1.3 Specific gravity (G_s)

The specific gravity (G_s), of a soil particle is defined as the ratio of its mass to the mass of an equal volume of water at 4°C. The average specific gravity

of a given lunar soil is related to the relative proportions of different particle types, i.e., basalts, anorthosites, mineral fragments, and glasses. Also, the porosity of the particles has a significant influence on the specific gravity values of the lunar soils. The specific gravity of the lunar soils and simulants was determined by performing various techniques such as nitrogen, helium, water, and air pycnometer, and suspension in a density gradient. The measured specific gravity value of the overall lunar soil is in the range of 2.90-3.25^{12,13}. Carrier *et al.*¹³ suggested using a specific gravity value of 3.1 for general scientific and engineering analyses of lunar soils. The measured specific gravity values (Table 1) 2.90 and 2.94 of the mare soil simulants JSC-1 and KLS-1 are falling within lunar soil specific gravity values^{16,19,20}. But, the other two mare soil simulants (BP-1 & DNA-1A)^{21,22} values are lower than the values of the lunar soils. When comparing the values of the highland soil simulants, the NAO-1 value match with the lunar soils, and NU-LHT-2M value^{17,18} found lower than the lunar soils. It is observed that the variation in specific gravity values between the simulants is due to the difference in particle size and porosity¹³.

3.1.4 Atterberg's limits and Classification

In addition to particle size distribution tests, Atterberg limit tests were carried out to determine the plastic and liquid limits of the fines since fines in

lunar regolith are more than 50 percent²³. Also, the Unified Soil Classification System (USCS) system is based on the particle size distribution and Atterberg's limits if the fines are more than 50 percent²³. Referring to the findings of the lunar soils in the lunar sourcebook¹³, the lunar soils have non-plastic nature though it consists of more than 50 percent fines (silt). According to the USCS³⁹, the lunar soils are classified as silty sand to sandy silt: SW-SM to ML^{12,13}. The test results revealed that the simulant exhibits very little plasticity, whereas the test results were inconsistent for multiple tests. Therefore, it is noticed that the simulants (mare and highland) were also showing similar behavior of the lunar soils and classified as silty sand (SM)^{16,17,18,19,21,22}.

3.1.5 Bulk density and porosity

One of the most important parameters associated with lunar soils is the bulk density (ρ), defined as the mass of material per unit volume. The in-situ bulk density of lunar soil is a fundamental property. It influences bearing capacity, slope stability, seismic velocity, thermal conductivity, electrical resistivity, and the depth of penetration of ionizing radiation¹³. The early inferred bulk density of the lunar soil was based on the remote sensing data, robotic measurements on the surface, astronaut's boot-prints, vehicle tracks, and boulder tracks. After the beginning of Apollo, core tube samples of lunar soil were returned that permitted

Table 1 — Geotechnical Properties of the lunar soil and simulants

Geotechnical Properties	Lunar Soil & Lunar Soil Simulants					Lunar Highland Simulants	
	Lunar Soil	JSC-1*	KLS-1**	BP-1#	DNA-1A##	NT-LHT-2M+	NAO-1++
Specific Gravity, G_s	2.90 – 3.24	2.90	2.94	2.81	2.70	2.74	2.92
Fines, %	40 – 65	40 - 50	48	28	30	42	48
Coefficient of uniformity, C_u	16	7.5	12.5	10.47	5	8.46	18
Coefficient of curvature, C_c	1.2	1.12	1.28	2.61	1.3	1.54	2.34
Soil Classification (USCS)	SM/ML	SM	SM	SM	SM	SM	SM
Bulk density, ρ (g/cm ³)	1.50 – 1.66	1.55 – 1.65	1.81	1.63	1.33	1.75	1.93
Relative density, %	60 – 65	40 - 60	60	55	70	65	75
Maximum density, ρ_{max} (g/cm ³)	1.51 – 1.93	1.80	2.02	1.86	1.57	2.05	2.10
Minimum density, ρ_{min} (g/cm ³)	0.87 – 1.36	1.33	1.58	1.43	0.98	1.36	1.41
Maximum Void Ratio, e_{max}	1.21 – 2.37	1.18	0.980	3.20	1.76	1.004	1.002
Minimum Void Ratio, e_{min}	0.67 – 0.94	0.61	0.460	1.10	0.72	0.332	0.420
Maximum dry density, ρ_{dmax} (g/cm ³)	NIL	NIL	NIL	NIL	NIL	1.87	NIL
Optimum moisture content, %	NIL	NIL	NIL	NIL	NIL	15.2	NIL
Average porosity, n (%)	52 – 46	49	40	64	55	37	40
Cohesion stress, c (kPa)	0.1 – 1	1.00	1.85	2	0	0.1	0
Angle of internal friction, ϕ (deg)	30 – 50	45	44.9	45	44 – 47	38.5	46.6
Compression Index, C_c	0.01 – 0.11	0.26	0.29	0.042	0.224	0.060	NIL
Recompression Index, C_r or Swelling Index, C_s	0.000 – 0.013	NIL	0.004	0.006	0.013	0.001	NIL

Data from *McKay *et al.*¹⁹, **Ryu *et al.*¹⁶, #Florez *et al.*²¹, ##Marzulli and Cafaro²², Zeng *et al.*¹⁷ and Li *et al.*¹⁸

unambiguous measurements of the in-situ bulk density. Bulk density measurements have been made with direct and indirect methods. Direct measurements can be made using core tube samples. The bulk density for any soil can be calculated using the relationship (Eq. 8) between bulk density (ρ), void ratio e , and specific gravity G_s as follows:

$$\rho = \frac{G_s(1+w)\rho_w}{(1+e)} \quad \dots (8)$$

where, ρ_w = density of water and w = water content.

The in-situ porosity (n) of lunar soil is calculated by combining the best estimates of bulk density and specific gravity as,

$$n = 1 - \frac{\rho}{G\rho_w} \quad \dots (9)$$

At present, the best estimate for the average bulk density^{12,40} of the top 15 cm of lunar soil is $1.50 \pm 0.05 \text{ g/cm}^3$, and of the top 60 cm, $1.66 \pm 0.05 \text{ g/cm}^3$. The reported⁴⁰⁻⁴² average porosity of the lunar soil is 52% for the depth of top 15cm, 49% at 30 cm depth, and 46% at a depth of 60cm. It is observed that the (Table 1) mare soil simulants made with volcanic ash (JSC-1, BP-1) having a better bulk density value, which is comparatively closer to the lunar soils, and DNA-1A is having a low bulk density value compare to all the lunar simulants. Also, it seems that the simulants developed from the rocks, especially highland simulants (NU-LHT-1M and NAO-1) are having higher bulk density values, which is because of the lesser pores in the particles. The mare soil simulant KLS-1 is also having a similar property since it is made from basaltic rocks.

3.1.6 Relative density

Relative density is the most significant variable which influences the strength and compressibility behavior of the soil or lunar soil^{13,30,31,32,42,43}. The relative density of the lunar soil is vital to vehicle mobility and ISRU operations as it directly affects the shear strength of the soil¹⁷. The relative density generally refers to the degree of particle packing (which is particle size and shape distribution dependent) of a soil^{17,21}. In general, relative density or density index is defined as the ratio of the difference between the void ratio of the soil in its loosest state (e_{\max}) and natural state (e) to the difference between the void ratio in its loosest (e_{\max}) and densest states (e_{\min}). The relative density can be measured using the below Eq. (10),

$$D_R = \frac{(e_{\max} - e)}{(e_{\max} - e_{\min})} \times 100 \quad \dots (10)$$

The relative density can also be calculated from the known or measured bulk density of the soil sample by using the Eq. (11) given as,

$$D_R = \frac{\rho_{\max}(\rho - \rho_{\min})}{\rho(\rho_{\max} - \rho_{\min})} \times 100 \quad \dots (11)$$

where, ρ_{\max} = maximum bulk density; ρ_{\min} = minimum bulk density; ρ = bulk density of the sample in its natural state. The in-situ relative density of lunar soil is about 65% (medium to dense) in the top 15 cm, increasing to more than 90% (very dense) below a depth of 30 cm^{12,13,39}. It seems that the lunar soils are extensively densified and shaken due to the frequent impact of meteoroids¹³. The reported minimum and maximum density range¹³ of the lunar soil was $0.87\text{-}1.36 \text{ g/cm}^3$ and $1.51\text{-}1.93 \text{ g/cm}^3$, whereas the corresponding reported minimum and maximum void ratio values are 0.67-0.94 and 1.21-2.34. The calculated relative density of the mare soil simulants (JSC-1, BP-1, KLS-1 & DNA-1A) was in the range of 55-70, and for highland, soil simulants (NU-LHT-2M & NAO-1) were 65-75 (Table 1). Also, the measured void ratio values of the lunar mare soil simulants were higher than the highland soil simulants. It denotes that the highland simulants have better packing arrangements, which results in lesser porosity during the compaction and having better particle size distribution and shape than the mare soil simulants. Also, it should be pointed out that in-situ test results were reported here for lunar regolith rather than ASTM standard laboratory tests, which leads to the variation in test results of the simulants¹⁷.

3.1.7 Compaction

This test was performed to find the best way, dry to wet, to achieve compaction for simulants when preparing soil samples in a soil bin, to simulate extreme conditions that may be encountered on the Moon¹⁷. In order to find an effective method to achieve maximum density and to find the influence of water on maximum density, a proctor compaction test was performed at a different water content with standardized compaction energy. The water content of the soil has a significant influence on the degree of compaction that can be achieved⁴⁴. In comparison to the maximum dry density achieved by vibration and from proctor compaction of the simulant, NU-LHT-2M is lower. It is observed that the reason for the lower density in the proctor compaction test is due to

the little plasticity of the fines (42%) present in the simulant. The same kind of behavior might be found in other lunar simulants due to the presence of fines of 30-48%. Therefore the vibration method with vertical surcharge is much more effective than proctor compaction to produce maximum density on the lunar surface.

3.2 Geo-mechanical properties

Understanding the geomechanical behavior of the lunar soil is predominant to the point when designing lunar structures, lander, rover, and other IRSU related vehicles that involve large quantities of lunar soil. The geomechanical properties such as shear strength, compressibility, and trafficability appear to be dominated by the particle size distribution, particle shape, and packing characteristics (density, void ratio) of lunar soils. A clear review of the geomechanical behavior of the lunar simulants with lunar soils enables the development of simulants for integration and IRSU related studies.

3.2.1 Shear strength

The shear strength influences the bearing capacity, slope stability, trafficability, and the astronaut's ease of movement of the soil or lunar soils^{12,13,41,42}. The design of wheel and lunar soil-wheel interaction studies are more dependent on the shear strength parameters (Cohesion and Angle of internal Friction)¹⁻⁵. In general, under Earth's gravitational conditions, the magnitude of cohesion is small compared to frictional effects. The cohesive properties of lunar soil seem small in earth conditions, but their significance in lunar gravity may be more notable. The Mohr-Coulomb failure criterion used for calculating the shear strength is expressed in the equation (12),

$$\tau = c + \sigma \tan \phi \quad \dots (12)$$

Where, τ is the shear strength on the failure plane, σ is the normal stress on the failure plane, c is the cohesion of the soil, and ϕ is the angle of internal friction. Therefore, the shear strength consists of two components: a cohesive component independent of the applied stress and a frictional component directly proportional to the normal stress (i.e., the stress that is perpendicular to the failure surface). Mitchel *et al.*¹² and Carrier *et al.*¹³ done multiple triaxial tests on lunar soils for different relative densities and confining pressures and reported the angle of internal friction and cohesion values as 30°-50° and 0.1-1 kPa from the best estimate of the Apollo model. Also, the reported best estimate of the Surveyor model values

of ϕ and c ranges from 35°-37° and 0.35-0.70 kPa. The given range of ϕ and c values includes the lunar samples collected at various depths on lunar regolith and tested. The values are the best estimates from the triaxial test results.

The same kind of procedure was followed to determine the shear strength parameters of the lunar simulants. The determined angle of internal friction values of both the type of simulants was lies between the given ranges of the lunar soils. The measured cohesion value of the simulants is too low to make any meaningful conclusion and consistent for typical silty sands (SM). But in comparison, the cohesion value (Table 1) of the mare soil simulants (JSC-1, KLS-1 & BP-1) were considerably higher than the lunar soils and in the range of 1-1.84. Also, the highland soil simulant NU-LHT-2M and NAO-1 values (Table 1) are matching with the reported lunar soil values. It is understood that the highland soil simulants have better similarity in shear strength behavior with the lunar soils than mare soil simulants. The higher cohesion value of the mare soil simulants (JSC-1, KLS-1 & BP-1) is due to the higher bulk density and low plasticity of the volcanic ash particles of the simulants. Seeing the bulk density of both highland soil simulants (NU-LHT-2M & NAO-1) is also higher than the lunar soils, but the determined cohesion values are low. This is due to the presence of rock particles (anorthosite) possessing non-plasticity behavior. It is inferred that all the laboratory tests on returned lunar soil samples suffer from the following limitations: (1) disturbance: the samples were sieved, remolded, and recompacted prior to testing; (2) size: the samples were small (to very small) by terrestrial testing standards; and (3) stress: unavoidably, the confining stresses applied to the samples were one to two orders of magnitude greater than the in situ lunar stresses. The last point appears to be especially significant. Under the low stresses present near the lunar surface, irregular and reentrant soil particles tend to interlock, producing a usually high shear strength.

3.2.3 Compressibility

The compressibility behavior of soil is one of the important parameters, which should be considered for the design of rover and lander wheel and wheel-soil interaction studies^{45,46}. Compressibility describes the volume change and densification that occurs when the confining stress or vertical load is applied to the soil. Compression of the soil results from particle slippage

and reorientation at low stress or low initial density. Also, the particle deformation and breakage at high stress or high density¹³. One dimensional compression test was performed, and the compression index (C_c) and recompression index (C_r) of the lunar soil was determined and reported as 0.01-0.11 and 0.000-0.013, respectively^{12,13}. The results denote that the lunar soil compresses more, swells slightly, and rebounds elastically. The formula used to calculate the compression index and swelling index is given in the Eqs (13 & 14). Equations 13 and 14 pertain to loading and unloading curves, respectively.

$$C_c = \frac{e_1 - e_2}{\log \left(\frac{P_2}{P_1} \right)} \quad \dots (13)$$

$$C_s = \frac{e_1 - e_2}{\log \left(\frac{P_2}{P_1} \right)} \quad \dots (14)$$

where, e_1 and e_2 are the void ratios corresponding to the applied pressures P_1 and P_2 . The compressibility index values of the JSC-1, KLS-1, and DNA-1A are 0.26, 0.29, and 0.224 are showing higher compression than the actual lunar soils, which is reported in the lunar sourcebook by Carrier *et al.*¹³ The reason behind this is due to the packing of the particles when the soil gets densified during compression. The mare soil simulants are having a variation in particle gradation with the lunar soils and made from volcanic ash, which normally tends to more compression. The compressibility of lunar soil has been compared with that of basaltic simulants by Mitchell *et al.*¹² and Carrier *et al.*¹³. In both cases, it was found that lunar soil is slightly more compressible than the simulant, regardless of whether the two soils are compared at the same void ratio or the same relative density. It is noted that the basaltic simulant compress under relatively low confining stress. Thus, the intragranular and subgranular porosities also influence the compressibility of lunar soil¹³. This is validated by comparing the lunar highland soil simulant (NU-LHT-2M) value 0.060, which is made from anorthosite rocks and having similar gradation with lunar soils. It denotes that the compression behavior of the mare soil simulants is higher than the highland soil simulants. Also, the determined recompression index of both mare (BP-1, KLS-1 & DNA-1A) and highland soil simulant (NU-LHT-2M) are falling within the range given for the actual lunar soils¹³, and it denotes that the simulants have very low swelling nature^{16,17,18,19,21,22}.

3.2.4 Trafficability properties

Trafficability is defined as the capacity of soil to support a vehicle and provide sufficient traction for

movement¹³. The energy consumed by a wheeled vehicle operating on the lunar surface can be divided into three components: soil compaction, roughness, and elevation changes. Trafficability depends, in particular, on settlement due to soil compaction under the vehicle or rover weight. Soil compaction (sinkage) can be estimated from empirical Eqs (15 and 16) developed by Bekker (1969)⁴⁷,

$$P = kZ^n \quad \dots (15)$$

$$P = \left(\frac{k_c}{b} + k_\phi \right) Z^n \quad \dots (16)$$

where, P is the pressure, k is a modulus of inelastic deformation, Z is the soil depth, k_c and k_ϕ are moduli of deformation with respect to cohesion and friction, and n is the sinkage exponent. Soil compaction (sinkage) of the soil is influenced by the cohesive modulus of deformation (k_c), frictional modulus of deformation (k_ϕ), and sinkage exponent (n)^{12,13,48}. The structure of the lunar rover wheel and the interaction properties between the wheel and lunar soil have an important impact on the movement performance of the rover; understanding the above characteristics plays an important role in the rover^{1,4}. The reported cohesive modulus of deformation (k_c), frictional modulus of deformation (k_ϕ), and sinkage exponent (n) of the lunar soil^{12,13,48} are 1.40 kPa, 820 kPa and 0.8 to 1.2 respectively. Further vehicle trafficability estimates, the energy loss caused by roughness over a given distance is proportional to the speed⁴⁸. During the Lander Rover Vehicle (LRV) traverses on Apollo missions, this component of energy consumption amounted to about 0.0027 W-hr/km/kg, which is equivalent to climbing a smooth slope of 0.4°. This value is probably a fairly reasonable estimate for designing future manned vehicles, even for travel in rougher areas, because the speed in such regions will necessarily be reduced. Lower energy consumption could be attained if improved roads are constructed on the lunar surface; a value of practically zero could be used for a slow-moving uncrewed vehicle. Based on detailed wheel-soil interaction studies of lunar soils and some mare soil simulants, Costeset *et al.*⁴⁸ concluded that variations in the trafficability soil parameters had little influence on the energy consumption of the LRV. Altogether, the rover energy consumption caused by all lunar surface characteristics amounted to only about 0.01 W-hr/km/kg, or about 15% of the total mileage. The reported rover speed on the lunar surface was 6 – 7 km/hr¹³.

3.2.5 Bearing Capacity

The ability of soil to support an applied load, such as a vehicle, a structure, or even an astronaut, is defined as the bearing capacity. The bearing capacity is controlled by the soil density, its shear strength, and the size of the footing¹³. The bearing capacity of the lunar soil was estimated by Mitchell *et al.*¹² based on the equation (17),

$$q_{ult} = CN_c \xi_c + \rho g_M BN_{\gamma q} \xi_{\gamma q} \quad \dots (17)$$

where, ρ = density of soil; $g_m = 1.62 \text{ m/sec}^2$ (acceleration of gravity on the Moon); B = footing width; c = cohesion of soil; $N_c, N_{\gamma q}$ = bearing capacity factors, which are primarily dependent on the friction angle, ϕ , of the soil; and $\xi_c, \xi_{\gamma q}$ = shape factors. During the landing of Lunar Module Apollo 1, the diameter of the footpad was 1m. By considering the remaining parameters of the equation from the test results of the geotechnical properties of the lunar soil, it is estimated that the ultimate bearing capacity of the lunar soil was approximately 3000-11,000 kPa. But the actually transferred stress to the lunar soil from the landing pad was 5 kPa, and the factor of safety was 600 to 2200¹³. Furthermore, for larger footings, the ultimate bearing capacity is roughly proportional to the width. That means that the ultimate load (stress \times area) for a circular or square footing is proportional to the cube of its width. Consequently, the ultimate bearing capacity of the lunar surface is more than sufficient to support virtually any conceivable lunar modules, LRV and structure¹³.

3.2.6 Slope Stability

On Earth, slope failures are usually caused by fluctuations in the groundwater table, erosion from running water, and occasionally tectonic activity. The triggering mechanism is presumed to be the seismic vibrations produced by a meteoroid impact, but explanations of how the talus has been able to move such long distances are very speculative on the Moon. The absence of water greatly simplifies the analysis of slope stability on the Moon. The most common methods are based on limit equilibrium analysis of circular potential slip surfaces. The factor of safety (FoS) against slope failure can be reduced to the following Eq. (18),

$$FoS = N \frac{h\rho g_m}{c} \quad \dots (18)$$

where, ρ = density of soil, c = cohesion of soil, g_m = acceleration of gravity on the Moon, h = height of

slope, and N = stability number, which is a function of the friction angle, ϕ , of the soil and the slope angle, β . The constructed slope or vertical cut can be made using a factor of safety of 1.5, which is more than adequate for design purposes. The calculations show that a vertical cut could be made in lunar soil to a depth of about 3 m, and a slope of 6° could be maintained to a depth of about 10 m¹³. Carrier *et al.*¹³ concluded that lateral movement of soil was occurring on slopes flatter than the angle of repose. While some of this movement could be attributed to meteoroid impacts, they proposed that a portion was caused by some kind of soil creep of problematic origin.

4 Conclusions

A typical review has been done on the chemical composition, mineralogy, geotechnical and geomechanical properties between the mare and highland soil simulants. The properties have also been compared with the actual lunar soils. Based on this review, the following conclusions have been drawn.

- 1 The reported mare and highland soil simulants have been developed to represent the actual lunar soil properties and possessing a comparatively similar behavior to the lunar soils. When looking into depth, the difference in properties between the mare and highland soil simulants with the lunar soils has been found, and that should be incorporated for the newly developing simulants.
- 2 The chemical composition of the mare soil simulants and highland soil simulants is comparatively similar to their respective mare and highland soils. It is understood that simulants have to be developed from the basaltic rocks/ashes and anorthosite rocks, respectively, to possess a similar composition of the mare and highland soil.
- 3 The particle size distribution of the highland soil simulants (NU-LHT-2M & NAO-1) is similar to the lunar soils, whereas the mare soil simulants (JSC-1, BP-1 & DNA-1A) have acceptable variation. The variation may be rectified when different size volcanic ash particles have been mixed together and used. The particles pulverized into different sizes and mixed together to get optimum proportion will have better gradation with the lunar soils.
- 4 The lunar soils have varied particle morphology. The mare soil simulants (JSC-1, BP-1 & DNA-1A) having a similar morphology with the lunar soils to the highland simulants (NU-LHT-2M and NAO-1).

- 5 The compaction level of the lunar regolith is different from that commonly seen in the terrestrial environment. The surface soil is in a very low-density state, and the underlying soil is highly compacted. In addition, with simulants, the density range will be different from the lunar regolith, and like behavior will not correspond directly with bulk density. It is important to account for both of these factors.
- 6 The friction and cohesion values have to be determined at low confining pressures since the lunar soil having a loose density at the top of the lunar surface.
- 7 The geotechnical properties of the simulants have to be assessed under the lunar environmental conditions because the extreme environmental condition of the Moon influence the surface properties of the particles, increase friction, and, in turn, strengthens themes.
- 8 The dynamic properties of the simulants have to be determined under simulated moonquake conditions and incorporated for the design of lunar structures for futuristic lunar habitations. The stability analysis shows that the bearing capacity of the lunar soil is much more than the stress transferred from the lander and rovers to the lunar surface. Hence, the lunar regolith/soil is sufficient to support virtually any conceivable lunar modules, LRV, and structure.
- 9 From the slope stability analysis, the vertical cut could be made up to a depth of about 3 m, and the slope could be maintained at 60° to a depth of about 10 m on the lunar surface.
- 10 To obtain the accurate behavior of the simulants for the design of lander, rover, and wheel-soil interaction studies, the trafficability characteristic of the lunar soil simulants has to be assessed under the vacuum and reduced gravity conditions (1/6th of Earth gravity).
- 11 The available lunar highland simulants are very few. Hence it is essential to develop a new lunar highland simulant to emulate all the required properties and beneficial to complete the extensive research about the highlands and South Polar Region of the Moon.

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