Novelty Journals

ISSN 2394-7349

International Journal of Novel Research in Engineering and Science
Vol. 13, Issue 2, pp: (1-7), Month: September 2026 - February 2027, Available at: www.noveltyjournals.com

SelenEntropic Resilience: An Entropy-Based Assessment of Lunar Soil Stability Using NASA Data

Dr Nikolaos Toumasis

Faculty of Engineering and Applied Sciences / Cranfield University

DOI: https://doi.org/10.5281/zenodo.22259903

Published Date: 02-September-2026

Abstract: **Lunar regolith combines a wide compositional range, a broad and repeatedly reworked particle-size distribution, and depth-dependent shear strength, yet these three properties are almost always reported separately in the literature. This study applies Shannon entropy to two of these properties for five Apollo landing sites (12, 14, 15, 16 and 17): the bulk oxide composition of returned fines, and the dispersion of published particle-size statistics. A normalized compositional entropy and a granulometric variability index are computed for each site and combined into a composite SelenEntropic Resilience Index (SERI). Mare-influenced sites with a comparatively even mix of oxides score highest on compositional entropy, while the anorthosite-rich Apollo 17 soil, dominated by a single oxide group, scores lowest. Apollo 14 stands apart on the granulometric side, showing far greater dispersion in reported grain size than any other site, a pattern traceable to known sampling heterogeneity near Cone Crater ejecta. The resulting SERI values are discussed alongside independently reported lunar geotechnical parameters, bulk density, internal friction angle and cohesion, to indicate where compositional or granulometric disorder may warrant closer geotechnical attention before excavation, foundation work or in-situ resource utilization at a given site. The index is presented as a first-order screening tool built entirely from published NASA and peer-reviewed data, and the additional site-resolved sieve and shear-strength measurements needed to extend it into an operational design parameter are identified.**

Keywords: **Apollo regolith; compositional entropy; geotechnical stability; granulometry; in-situ resource utilization; lunar soil mechanics; particle-size distribution; Shannon entropy.**

I. INTRODUCTION

Interest in the mechanical behavior of lunar regolith has returned along with renewed lunar exploration, since landing pad design, rover trafficability, excavation for in-situ resource utilization (ISRU) and the durability of any surface structure all depend on how the soil responds to load. Direct measurement of these properties began during the Apollo missions between 1969 and 1972, using drive-tube and core sampling, penetrometer readings, and laboratory testing of returned samples. That data set was later consolidated in the Lunar Sourcebook [2] and in subsequent reviews of lunar soil mechanics [1], [3].

Existing characterizations of lunar soil generally report bulk density, shear strength and grain-size distribution as independent parameters, each tied to depth or to a specific landing site. Less attention has been paid to whether the degree of disorder in a soil's chemical mixture, or in its grain-size spread, carries any diagnostic value on its own. Shannon entropy offers a compact way to measure exactly that kind of disorder, and has been applied previously in sedimentology and materials science to describe mineral-assemblage diversity and granular packing. This study applies the same idea to lunar regolith, computing compositional entropy directly from published Apollo bulk-chemistry data and a granulometric variability index from published particle-size ranges, then combining both into a single composite index referred to here as the SelenEntropic Resilience Index (SERI).

International Journal of Novel Research in Engineering and Science
Vol. 13, Issue 2, pp: (1-7), Month: September 2026 - February 2027, Available at: www.noveltyjournals.com

The index is intended as an exploratory screening tool, not a validated geotechnical design parameter. Section V returns to this point directly and lists the additional per-site data that would be needed before SERI could be used operationally.

II. BACKGROUND

A. Formation and Maturity of Lunar Regolith

Lunar regolith results from billions of years of meteoritic and micrometeoritic bombardment acting on bedrock, a process that both fractures larger grains (comminution) and welds finer material into glass-bonded agglutinate particles. Carrier [4] found that grain-size distributions from Apollo 11, 12, 14 and 15 soils had reached a statistical steady state in which comminution and agglutination roughly balance, giving a median particle size clustering between 40 and 130 micrometers across sites of very different geology, with the full range of reported mean grain sizes spanning roughly 40 to 800 micrometers. Regolith maturity, the cumulative surface exposure time of a soil, is tracked through indices such as Is/FeO, the ratio of single-domain ferromagnetic iron to total iron, and correlates with higher agglutinate content and greater mixing of local and impact-transported material [5], [6]. This mixing is, in effect, an entropy-increasing process, which is part of the motivation for using an entropy metric here.

B. Geotechnical Properties of Lunar Soil

Bulk density of lunar soil rises from around 1.30 g/cm3 at the surface to an asymptotic value near 1.92 g/cm3 at depth, following a hyperbolic density-depth relationship fit to Apollo drive-tube and drill-core records [2], [1]. Shear-strength testing places the internal friction angle between roughly 30 and 50 degrees near the surface, increasing toward about 55 degrees within the first meter as relative density increases, with a cohesion component that is small at the surface (on the order of 0.1 to 1 kPa) but rises with depth, reaching approximately 2.2 kPa at 1 m and 4.3 kPa at 2 m according to NASA Johnson Space Center geotechnical summaries [10]. These properties together permit remarkably steep excavations: vertical trenches to about 3 m with a safety factor of 1.5, and 60-degree slopes to roughly 10 m [2].

C. Compositional Contrast Across Sites

The five sites examined span both mare basalt terrain, rich in iron and titanium oxides, and highland terrain, dominated by aluminum-rich anorthosite. Apollo 12 sampled mare basalt regolith with markedly higher TiO_2 and FeO than the highland sites, while Apollo 17 sampled a mixed valley setting with a strong anorthositic contribution and correspondingly low FeO. This contrast, documented since the earliest post-Apollo sample analyses [12], is the basis for the compositional entropy comparison in Section IV.

III. MATERIALS AND METHODS

A. Data Sources

All numerical inputs used in this study come from published NASA technical reports, NASA-funded peer-reviewed literature, or secondary compilations of that literature, as listed in Table I. No sample-level sieve or spectrometry results were generated for this study; where a source reports a range across sub-samples or across independent investigations, the full cited range is retained, and where a single value is required for a calculation, the arithmetic midpoint of that range is used and stated explicitly.

TABLE I. PRIMARY DATA SOURCES USED IN THIS STUDY

Property	Source(s)	Coverage
Oxide composition (wt%)	Lunar Sourcebook [2]; Papike et al. [12]; tabulation in [13]	Apollo 12, 14, 15, 16, 17
Particle-size (D50 / mean) statistics	NASA RP-1265 Lunar Soils Grain Size Catalog [11]; Carrier [1]	Apollo 11-17 fines
Bulk density vs. depth	Carrier, Olhoeft & Mendell [3]; Carrier [1]	Composite, all sites
Cohesion and friction angle	Mitchell et al. [7], [8]; NASA JSC geotechnical summary [10]	Composite, all sites

TABLE II. BULK OXIDE COMPOSITION (WT%) OF APOLLO REGOLITH FINES

Oxide	Apollo 12	Apollo 14	Apollo 15	Apollo 16	Apollo 17
SiO2	42.2	46.3	48.1	46.8	45.1
TiO2	7.8	3	1.7	1.2	0.54
Al2O3	13.6	12.9	17.4	14.6	27.3
FeO	15.3	15.1	10.4	14.3	5.1
MnO	0.2	0.22	0.14	0.19	0.3
MgO	7.8	9.3	9.4	11.5	5.7
CaO	11.9	10.7	10.7	10.8	15.7
Na2O	0.47	0.54	0.7	0.39	0.46
K2O	0.16	0.31	0.55	0.21	0.17
P2O5	0.05	0.4	0.51	0.18	0.11

Compiled after Heiken, Vaniman and French [2] and secondary tabulation in [13].

TABLE III. PUBLISHED PARTICLE-SIZE (D50 OR MEAN) RANGES BY SITE

Site	Range (micrometers)	Statistic	Note
Apollo 12	42 - 94	Median (D50)	Mare basalt regolith
Apollo 14	75 - 802	Median (D50)	Wide range; local heterogeneity near Cone Crater ejecta
Apollo 15	51 - 108	Median (D50)	Mare / highland boundary
Apollo 16	101 - 268	Mean	Highland (Descartes / Cayley)
Apollo 17	42 - 166	Mean	Highland-valley mixed setting

Source: [11], with ranges as tabulated in [13] from multiple independent sieve studies per site.

B. Compositional Shannon Entropy

For a sample with n reported oxide mass fractions p1 through pn, normalized so the fractions sum to one, the Shannon entropy is given by:

$$H_{comp} = -\Sigma\, p_i \cdot \log_2(p_i), \quad i = 1 \text{ to } n$$

Hcomp reaches its maximum, Hmax = log2(n), when mass is distributed evenly across all n oxides, and falls toward zero as one oxide comes to dominate the mixture. The normalized form Hnorm = Hcomp / Hmax is reported so that results are comparable regardless of how many oxides happen to be tabulated. With n = 10 oxides (SiO2, TiO2, Al2O3, FeO, MnO, MgO, CaO, Na2O, K2O, P2O5), Hmax works out to log2(10) = 3.322 bits.

C. Granulometric Variability Index

Per-mission sieve-fraction histograms are not consistently available in the compiled secondary literature reviewed for this study, so a proxy for grain-size disorder is built instead from the published minimum-to-maximum range of reported median or mean particle size at each site. For a site with reported range [dmin, dmax] in micrometers, the octave spread is defined as:

$$S = \log_2(d_{max} / d_{min})$$

S measures, in doublings, how widely the reported central particle size varies across independent studies and sub-samples at a given site, which is itself a signal of local heterogeneity: a soil sampled consistently across studies would show dmin approximately equal to dmax and S close to zero. S is min-max normalized across the five sites to obtain the granulometric variability index, GVI, on a 0 to 1 scale, where 1 marks the site with the greatest dispersion (Apollo 14, in this data set) and 0 marks the least (Apollo 15). GVI should be read as a between-study dispersion proxy rather than a true within-sample particle-size entropy; Section V identifies the sieve-fraction data that would allow the latter to be computed directly.

International Journal of Novel Research in Engineering and Science
Vol. 13, Issue 2, pp: (1-7), Month: September 2026 - February 2027, Available at: www.noveltyjournals.com

D. Composite SelenEntropic Resilience Index

SERI is defined on a 0 to 100 scale as a weighted combination of compositional order, (1 - Hnorm), and granulometric order, (1 - GVI):

$$SERI = 100 \cdot [\alpha \cdot (1 - Hnorm) + \beta \cdot (1 - GVI)], \quad \alpha + \beta = 1$$

A baseline weighting of α = 0.6 and β = 0.4 is adopted, reflecting that compositional entropy is calculated from a directly measured, site-specific bulk-chemistry data set, while GVI rests on a cross-study range proxy of lower resolution. All entropy calculations were carried out in Python (version 3.11) using standard scientific libraries, and intermediate values are reported to three decimal places for traceability. Section IV reports SERI under this baseline weighting.

SERI deliberately excludes shear strength, cohesion and bulk density from the numerical index itself, because the available literature reports these parameters as general lunar-regolith functions of depth rather than resolved separately by site. Bulk density, friction angle and cohesion are instead treated as a shared geotechnical backdrop, discussed qualitatively alongside the site-resolved entropy metrics in Section IV, rather than folded into a site-comparative index where they would carry a false precision. This is identified as the main limitation of the framework in its present form.

IV. RESULTS AND DISCUSSION

A. Compositional Entropy

Table IV reports the Shannon entropy of oxide composition for each site, computed directly from Table II.

TABLE IV. COMPOSITIONAL SHANNON ENTROPY BY SITE

Site	Sum of tabulated oxides (wt%)	Hcomp (bits)	Hnorm	Gini-Simpson diversity
Apollo 12	99.48	2.350	0.707	0.751
Apollo 14	98.77	2.251	0.678	0.718
Apollo 15	99.60	2.199	0.662	0.705
Apollo 16	100.17	2.184	0.657	0.715
Apollo 17	100.48	2.029	0.611	0.694

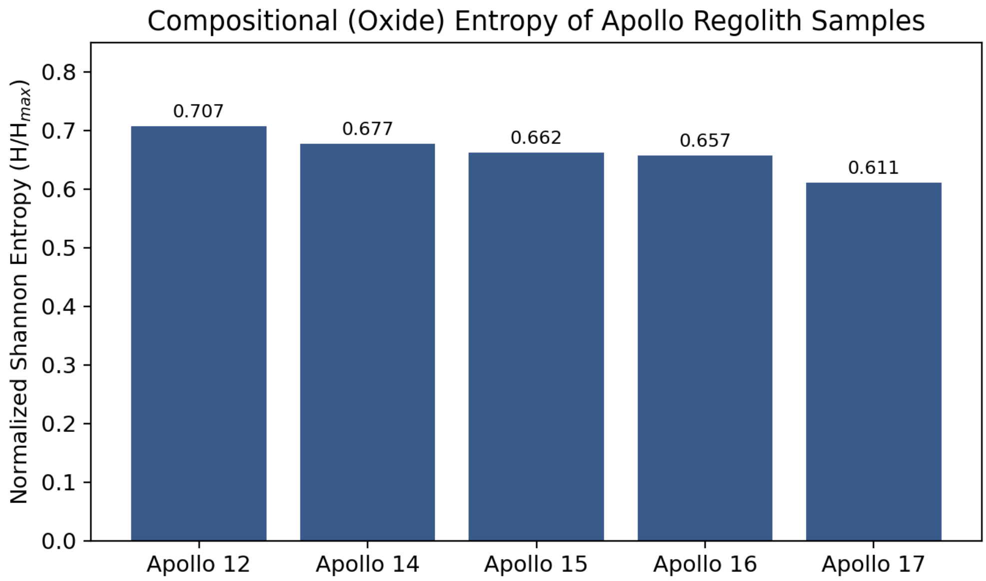

Fig. 1. Normalized compositional entropy by Apollo site.

The ranking, from most to least compositionally even, runs Apollo 12, 14, 15, 16, 17, and tracks known site geology reasonably closely. Apollo 12's mare basalt fines carry sizeable, comparably scaled contributions from SiO2, FeO, Al2O3,

International Journal of Novel Research in Engineering and Science
Vol. 13, Issue 2, pp: (1-7), Month: September 2026 - February 2027, Available at: www.noveltyjournals.com

TiO2 and CaO, whereas Apollo 17's high Al2O3 content (27.3 wt%, reflecting its anorthositic highland component) increasingly dominates the mass budget and pulls entropy down. This is consistent with the ranking behaving as a genuine diversity measure rather than an artifact of how the normalization was set up.

B. Granulometric Variability

Table V converts the particle-size ranges from Table III into octave spread and the normalized GVI used in the composite index.

TABLE V. OCTAVE SPREAD AND NORMALIZED GRANULOMETRIC VARIABILITY INDEX

Site	Range (micrometers)	Octave spread, S	GVI
Apollo 12	42 - 94	1.162	0.034
Apollo 14	75 - 802	3.419	1.000
Apollo 15	51 - 108	1.082	0.000
Apollo 16	101 - 268	1.408	0.139
Apollo 17	42 - 166	1.983	0.385

Apollo 14 is a clear outlier here, spanning more than three doublings of reported central grain size across independent studies. This matches the well-documented finding that Apollo 14 soils clumped during sieving and that a relatively small, non-uniform set of samples was analyzed near Cone Crater ejecta [4], producing a much wider inter-study spread than at any of the other four sites.

C. Composite SERI

Table VI and Fig. 2 give SERI for each site under the baseline weighting (α = 0.6, β = 0.4).

TABLE VI. COMPOSITE SERI BY SITE (BASELINE WEIGHTING)

Site	Hnorm	GVI	SERI (0-100)
Apollo 15	0.662	0.000	60.29
Apollo 12	0.707	0.034	56.19
Apollo 16	0.657	0.139	54.99
Apollo 17	0.611	0.385	47.95
Apollo 14	0.678	1.000	19.35

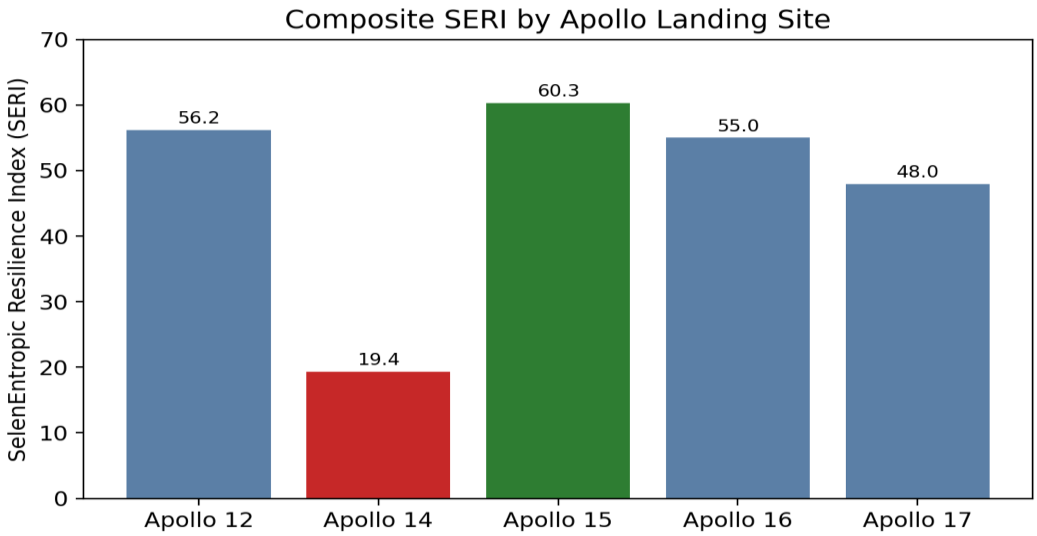

Fig. 2. Composite SERI by site.

Two points stand out. First, Apollo 15 and Apollo 12, both mare or mare-adjacent sites with comparatively homogeneous, well-sampled soils, score highest. Second, Apollo 14's low score is driven almost entirely by the granulometric term rather than the compositional term, which is mid-range for that site; a composite score reported without its two components would obscure this distinction. For that reason, Hnorm and GVI are reported alongside SERI throughout rather than SERI alone.

D. Geological Interpretation

The compositional entropy ranking fits established lunar petrology reasonably well. Mare basalt regolith mixes pyroxene, olivine, ilmenite and plagioclase-derived material in relatively balanced proportions, which raises Hcomp. Highland-dominated regolith, and particularly Apollo 17's anorthositic component, is increasingly dominated by plagioclase feldspar, rich in Al_2O_3 and CaO but poor in FeO, which concentrates mass in fewer oxides and lowers Hcomp. This gives a compact scalar summary of the mare/highland compositional split that has been documented since the earliest Apollo sample studies [12].

E. Relating Entropy to Geotechnical Behavior

Site-resolved shear-strength data are not available in the literature reviewed for this study, so SERI cannot yet be statistically correlated against measured cohesion or friction angle; that remains a limitation rather than a demonstrated result. Qualitatively, though, the general lunar geotechnical picture, bulk density rising from 1.30 to 1.92 g/cm3 with depth, friction angle rising toward 55 degrees, cohesion rising from roughly 0.1 to 4.3 kPa over the first two meters, describes a soil whose strength comes mainly from particle packing and interlocking rather than chemical bonding. In that kind of material, a site with high grain-size dispersion, such as Apollo 14, plausibly carries more uncertainty for predicting bearing capacity or trench stability at an unsampled point nearby, even where average reported strength values look similar to other sites, since a broadly graded and locally variable soil packs less uniformly than a narrowly graded one. This is the practical case for treating GVI, and by extension SERI, as a pre-screening flag indicating where additional local geotechnical survey work would be most useful, not as a substitute for direct measurement.

F. Comparison with Other Planetary Regolith

Recent Chang'e-6 far-side samples have been reported with a notably lower bulk density, about 0.983 g/cm3, than typical Apollo, Luna or Chang'e-5 near-side regolith, which ranges from about 1.1 to 2.1 g/cm3, suggesting a more porous soil structure at that site [14]. This is a reminder that the entropy values computed here for five near-side Apollo sites should not be extended to the lunar surface as a whole; applying the same framework to far-side or permanently shadowed polar regolith, where composition, porosity and volatile content all differ, is a natural next step rather than an assumption made here.

G. Practical Implications

For oxygen and metal extraction, compositional entropy has a fairly direct reading. Low-entropy, Al_2O_3-concentrated highland regolith, as at Apollo 16 and 17, may simplify some extraction chemistries by reducing the number of significant co-reactant oxides, while higher-entropy mare regolith of the Apollo 12 type offers a more balanced multi-metal feedstock (iron, titanium, magnesium) at the cost of more complex separation. For construction siting, the granulometric variability flagged by GVI suggests that Cone-Crater-ejecta-influenced terrain of the Apollo 14 type would benefit from denser local sampling before a specific excavation or foundation design is committed to, regardless of whether the regional average strength parameters look favorable.

V. CONCLUSION

This study computed Shannon entropy over published Apollo bulk-oxide compositions and built a granulometric variability index from published particle-size ranges, combining both into a composite SelenEntropic Resilience Index (SERI) for five Apollo landing sites. The resulting scores separate the sites in a way consistent with known lunar geology: compositionally balanced mare regolith and grain-size-homogeneous sites score highest, while Apollo 14 scores lowest because of its documented local heterogeneity, a result driven specifically by its granulometric rather than its compositional entropy. Reporting the two entropy components separately, rather than SERI alone, is what makes that distinction visible, and is recommended for any future use of the index.

Four limitations define the immediate next steps for this line of work. The granulometric variability index used here is a cross-study dispersion proxy rather than a true within-sample particle-size entropy; recomputing it from the sieve-fraction weight percentages tabulated in the NASA Lunar Soils Grain Size Catalog for each individual sample would allow a genuine per-sample grain-size entropy to replace the current proxy. The geotechnical parameters used for interpretation, cohesion, friction angle and density, are composite multi-site averages rather than site-resolved values; the original Apollo Soil Mechanics Experiment (S-200) penetrometer and drive-tube records would be needed to extend SERI into a fully three-component index. The weighting used to combine the two entropy terms ($\alpha = 0.6$, $\beta = 0.4$) is a stated, reasoned choice rather than one fit to independent stability outcomes, and a validation study correlating SERI against measured trafficability or excavation performance would be required before the index could be used for mission planning rather than hypothesis generation. Finally, this study covers only five near-side Apollo sites; extending the same method to Luna, Chang'e-5/6 and future polar samples would test whether the entropy-geology relationships identified here generalize beyond the sites studied. With these extensions, SERI has a reasonable path from a first-order screening index toward a more operationally useful geotechnical planning tool for future lunar surface missions.

ACKNOWLEDGMENT

The author(s) gratefully acknowledge the public availability of NASA Technical Reports Server (NTRS) archives and Lunar Sourcebook data, without which the compiled analysis in this paper would not have been possible.

REFERENCES

[1] W. D. Carrier III, "Particle size distribution of lunar soil," Journal of Geotechnical and Geoenvironmental Engineering, vol. 129, no. 10, pp. 956-959, 2003.

[2] G. Heiken, D. Vaniman, and B. M. French, Eds., Lunar Sourcebook: A User's Guide to the Moon. Cambridge, U.K.: Cambridge University Press, 1991.

[3] W. D. Carrier III, G. R. Olhoeft, and W. Mendell, "Physical properties of the lunar surface," in Lunar Sourcebook, G. Heiken, D. Vaniman, and B. M. French, Eds. Cambridge, U.K.: Cambridge University Press, 1991, pp. 475-594.

[4] W. D. Carrier III, "Lunar soil grain size distribution," The Moon, vol. 6, no. 3-4, pp. 250-263, 1973.

[5] R. V. Morris, "In-situ reworking (gardening) of lunar surface soils: Some concepts and Is/FeO compilation," in Proc. 9th Lunar and Planetary Science Conf., 1978, pp. 2287-2297.

[6] R. V. Morris, "Origins and size distribution of metallic iron particles in the lunar regolith," in Proc. 11th Lunar and Planetary Science Conf., 1980, pp. 1697-1712.

[7] J. K. Mitchell, W. N. Houston, R. F. Scott, N. C. Costes, W. D. Carrier III, and L. G. Bromwell, "Mechanical properties of lunar soil: Density, porosity, cohesion, and angle of internal friction," in Proc. 3rd Lunar Science Conf., 1972, pp. 3235-3253.

[8] J. K. Mitchell, W. D. Carrier III, N. C. Costes, W. N. Houston, R. F. Scott, and H. J. Hovland, Apollo Soil Mechanics Experiment S-200, Final Report, NASA Contract NAS 9-11266, Space Sciences Laboratory, Univ. of California, Berkeley, 1974.

[9] J. K. Mitchell and K. B. Soga, Fundamentals of Soil Behavior, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2005.

[10] NASA Johnson Space Center, "Lunar geotechnical properties," Technical briefing, National Aeronautics and Space Administration, 2022.

[11] J. C. Graf, Lunar Soils Grain Size Catalog, NASA Reference Publication 1265, NASA Johnson Space Center, 1993.

[12] J. J. Papike, S. B. Simon, and J. C. Laul, "The lunar regolith: Chemistry, mineralogy, and petrology," Reviews of Geophysics, vol. 20, no. 4, pp. 761-826, 1991 (as republished/reviewed 1991).

[13] X. Zhang et al., "A comprehensive review of lunar-based manufacturing and construction," arXiv:2408.05823, 2024.

[14] C. Li et al., "Chang'e-6 lunar farside sample return: Bulk density and regolith composition," as reviewed in studies of lunar surface scattering and sputtering, arXiv:2602.16567, 2024/2026.