EVALUATION OF GEOPHYSICAL PROPERTIES OF THE LUNAR REGOLITH FOR THE DESIGN OF PRECURSOR SCIENTIFIC MISSIONS FOR THE SPACE EXPLORATION INITIATIVE

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ABSTRACT

A working knowledge of the physical parameters of the upper ten meters of the lunar regolith is crucial to the planning of experimentation, mining, resource utilization, and construction associated with future lunar bases. Scientific research literature pertaining to studies of the lunar surface, including results of Apollo experiments and exploration, have been reviewed to produce a summary of our present knowledge of the physical properties of the lunar regolith. Particular emphasis was placed on gaps in our understanding. The primary data source for this review has been Carrier *et al.* *(1)*.

The purpose of this review is to address the following questions: 1) With what frequency may boulders be encountered that represent hazards to lunar operations?; 2) How easy may lunar soil be excavated?; 3) How may explosives be used in excavation operations?; 4) What is the trafficability of the regolith?; 5) What problems may be encountered in mining (probably strip mining) of the regolith?; 6) What angle(s) of repose will be stable in excavation of the regolith?; 7) What layering may be encountered in the subsurface?; 8) Is our knowledge of the regolith site specific, or may it be applied generically to any site on the lunar surface?; 9) What data will be needed to characterize a site for a lunar base?; 10) How may the regolith properties modify the design of geophysical experiments from the lunar base?; 11) Are there terrestrial analogues for the geophysical properties of the lunar regolith?

Available data indicate that there is significant lateral heterogeneity in the lunar regolith. This heterogeneity exists both with respect to small-size particle distributions (<1 mm), which may affect bulk material properties, and with respect to the random distribution of large-sized particles (>100 mm), which need to be considered for mining and excavation operations. Vertical layering of the regolith is expected at most sites, and considerable vertical heterogeneity may also be expected. Detailed site-specific surveys are recommended at all sites where mining and excavation operations are planned. These surveys should include sub-surface profiling, for which radar techniques appear to be most easily adapted, to determine the density and distribution of large, consolidated particles. This profiling should also determine the degree of subsurface layering. Core samples will be required to determine small-sized particle properties if significant layering is recorded. Trafficability appears to be primarily restricted by surface topographic features, although problems of raising the loose surface regolith must be considered. These problems appear to be associated with ballistic trajectories associated with surface activities which disturb the surface, and with electrostatic attraction by the lighter particles to charged surfaces. No terrestrial analogue adequately covers the range of properties likely to be experienced in the lunar regolith, but analogues for different physical and mechanical properties may be found.

INTRODUCTION

The lunar regolith is a an essentially continuous layer, typically several meters in thickness, which covers the entire lunar surface *(2)*. Any surface activities on the Moon, and any geological studies of the Moon are therefore strongly affected by the properties of the regolith. It is a mantle of fragmental and unconsolidated rock material of highly varied character, ranging from very fine dust to blocks of several meters in diameter. All lunar landings (Apollo and Luna), and all photographic studies of the Moon indicate that the regolith completely covers the underlying bedrock, except perhaps where bedrock may be exposed on some very steep-sided crater walls and lava channels. The finer components of the lunar regolith (<10 mm) are often informally referred to as lunar "soil", but this term must be used carefully as there are fundamental differences between terrestrial regoliths, of which soils are one group, and the lunar regolith (see DIFFERENCES AMONG THE MODES OF FORMATION OF LUNAR AND TERRESTRIAL REGOLITHS below).

Basically the constitution of the lunar regolith is relatively simple in comparison with terrestrial regoliths. There are five basic particle types in the lunar regolith:

1) Crystalline rocks (fragments of multi-mineral rocks which formed by crystallization from silicate melt)
2) Minerals (fragments of individual mineral crystals)
3) Breccias (fragments of rocks which are themselves composed of an aggregate of other rock and mineral fragments)
4) Agglutinates (pulverized rock, mineral and glass fragments bonded together with glass)
5) Glasses (fragments, irregular masses and beads of amorphous silicates formed by rapid cooling of silicate melts)

Fewer than a hundred minerals have been identified in lunar samples, compared with several thousand minerals that have been identified on Earth. While we may expect new minerals to be identified with continuing lunar exploration, we may confidently extrapolate present knowledge of lunar mineralogy to indicate that the mineralogy of lunar crust is at least an order of magnitude simpler than terrestrial crustal mineralogy. The physical properties of the lunar regolith also fall into relatively limited ranges compared to those of terrestrial regoliths due to the relatively simple mineralogy, the absence of a significant atmosphere, and the lack of water, clay minerals, and organic material in the lunar regolith. The primary factors that affect the physical properties of the lunar regolith are the packing of the regolith (bulk and relative densities) and temperature.

Current scenarios for the establishment of a permanent manned base on the Moon require specific activities which interact with the regolith *(3)*. These activities include: 1) Use of regolith material to shield long-term working and habitation modules sufficiently to reduce radiation from the largest recorded solar flares to safe

levels; 2) Surface transportation across the regolith; 3) Excavation of regolith material for oxygen production, and in the future for other mining operations such as the production of rare isotopes, such as ^{3}He, implanted in the regolith by the solar wind. A number of specific questions need to be answered before the mechanics of these activities can be evaluated. These questions include: 1) With what frequency may boulders be encountered that represent hazards to lunar operations?; 2) How easy may lunar soil be excavated?; 3) How may explosives be used in excavation operations?; 4) What is the trafficability of the regolith?; 5) What problems may be encountered in mining (probably strip mining) of the regolith?; 6) What angle(s) of repose will be stable in excavation of the regolith?; 7) What layering may be encountered in the subsurface?; 8) Is our knowledge of the regolith site specific, or may it be applied generically to any site on the lunar surface?; 9) What data will be needed to characterize a site for a lunar base?; 10) How may the regolith properties modify the design of geophysical experiments from the lunar base?; 11) Are there terrestrial analogues for the geophysical properties of the lunar regolith? Physical properties of the lunar regolith have been measured in situ by robots and astronauts, in the laboratory on returned samples, and by remote sensing from the Earth's surface and from lunar orbit. This report summarizes these results as they apply to the establishment of a permanent manned lunar base, and uses these results to propose precursor scientific studies for the Space Exploration Initiative. For the purposes of this report, the discussion of physical properties has been limited to mechanical (geotechnical) properties, which include parameters which describe grain size and shape, densities, and other geotechnical properties. These data are primarily summarized from Carrier *et al* *(1)*. Other physical properties, which include elastic (seismic), electrical and electromagnetic, magnetic, and thermal properties will be considered in future work. The section on mechanical properties is followed by a discussion of the implications of these properties, the mode of formation of the regolith, and considerations for lunar base activities.

MECHANICAL (GEOTECHNICAL) PROPERTIES

The mechanical properties of the lunar regolith were of vital importance to design of the Apollo Lunar Module and there was significant concern regarding the implications of these properties until the first human footsteps were made on the Moon (1). Some of the major uncertainties resulted from lack of knowledge of the behavior of fragmental lunar material in the lunar vacuum. Predictions varied from a very hard surface due to "cold welding" of the fragments in the vacuum, to a very soft surface due to the very small grain size of the fragments. Our present experience is that the lunar surface is not very soft, nor very hard. The range of geotechnical properties of the lunar regolith are less than occur in the terrestrial regolith: There appear to be three sources of this difference: 1) Terrestrial geologic exogenic processes tend to produce well-sorted sediments; The primary lunar soil-forming process is meteorite impact, which produces a poorly-sorted regolith;

2) Geotechnical properties of terrestrial soils vary by orders of magnitude as a result of water, clay minerals, and organic materials, not present on Moon; 3) The range of minerals in lunar soils much less than on Earth, in fact a large portion of the soil is glass.

Geotechnical properties of lunar soil tend to fall in a fairly narrow range, and the most significant variable is the relative density. Most other physical properties of the lunar regolith also tend to fall in a relatively narrow range, the largest variations occurring in those properties dependant on the relative density.

Particle Size Distribution

The particle size distribution of a regolith controls to various degrees its strength, compressibility, optical, thermal, and elastic (seismic) properties. The size distribution of selected samples have been summarized by Carrier et al. (1). Care should be exercised in using these data as they were derived from biased samples in the sense that only the soil fraction of the regolith, fragments smaller than 1 cm, have been included in the particle size distribution analysis. The consequences of this biased sampling are discussed below.

Carrier (4) has interpreted these results to indicate that the bulk of lunar soil samples fall in fairly narrow range of particle size distribution. In general, these results indicate that the soil is a poorly sorted, silty sand to sandy silt. The median particle size in the <1 mm fraction is 40 to 130 microns, with an average of 70 microns. In practical terms this means that about half of the lunar soil by weight is finer than human eye can resolve. Roughly 10-20% of soil finer than 20 microns, and a thin layer of dust appears to adhere electrostatically to everything that comes in contact with the soil: spacesuits, tools, equipments, lenses. Carrier et al. (1) warn that "Housekeeping is a major challenge for operations on the lunar surface."

Regolith dust is clearly a factor which must be taken into account in lunar surface operations, but potential problems with large regolith fragments is not so clearly illustrated by these data. Even some of the samples listed by Carrier et al. (1) have a significant fraction of particles with grain sizes greater than 1 cm. The bulk of samples 15400 and 70180 consist of these large particles, which were excluded from the median grain size calculations. The magnitude of this problem is clear from an examination of almost any of the photographs taken on the lunar surface (e.g., (5), Figures 4.1 and 4.3). Many centimeter- to meter-sized fragments are visible in these photographs, and in places large fragments clearly constitute a significant portion of the regolith. There is a need for greater study of the size and frequency distribution of the larger regolith particles.

Particle Shapes

Shapes of the lunar regolith particles are highly variable, ranging from spherical to extremely angular. In general, particles are somewhat elongated and are

sub-angular to angular. Because of this elongation, particles tend to pack together with a preferred orientation of the long axes, and physical properties in situ are expected to be anisotropic. Particles are not compact, but have irregular, re-entrant surfaces, a feature which especially affects the shear strength of the regolith.

Studies of the average shape properties of the finer fraction of the regolith indicate that the particles have an average elongation of about 1.35 (ratio of the major and intermediate axes of the fragments), and aspect ratios for most of the particles are in the range of 0.4 to 0.7 (ratio of minor and major axes of an ellipse fitted to the particle shape by least squares). Most particles are therefore described as slightly-to-medium elongated. Measurements of particle roundness indicate that the particles are sub-angular to angular in shape.

Specific Gravity

The specific gravity of a soil particle is defined as the ratio of its mass to the mass of an equal volume of water at 4°C. Values for lunar soils range from 2.3 to >3.2 and Carrier *et al.* (1) recommend a representative value of 3.1 for general scientific and engineering purposes. In contrast, many terrestrial soils have a specific gravity of 2.7. The average specific gravity of a given lunar soil is related to the relative proportions of the different particle types which constitute the soil, i.e., the relative proportions of basalts, mineral fragments, breccias, agglutinates, and glasses.

Bulk Density and Porosity

The bulk density of a soil is defined as the mass of the material contained in unit volume (usually given in g cm^{-3} or Mg m^{-3}) Porosity is defined as the volume of void space in the material divided by its total volume. The *in situ* bulk density of a lunar soil is a fundamental property, influencing its bearing capacity, slope stability, seismic velocity, thermal conductivity, electrical resistivity, and the depth of penetration of ionizing radiation. Lunar regolith bulk density is highly variable, not only from site to site, but also from station to station, and even with depth in a single core. At present, the best estimate for the average bulk density of the top 150 mm of lunar soil is 1.50 $\pm$ 0.05 Mg m^{-3}, and of the top 600 mm, 1.66 $\pm$ 0.05 Mg m^{-3} (1). The average porosity in the top 300 mm of the surface is 49%. Bulk densities tend to be less variable below about 1 m, and the mean bulk density of a long core from Apollo 17 from a depth of 1 to 2 m is approximately 1.8 Mg m^{-3}. A variability of $\pm$ 0.15 Mg m^{-3} is shown in bulk density measurements on cores from Apollo 15, 16 and 17 at these depths (1), however, and this variability could be significant in lunar base engineering activities.

Relative Density

Relative density is a measure of the degree of particle packing of a granular

soil, such as lunar soil. In situ relative density is another parameter which influences the physical and geophysical properties of a soil, and some of these properties may vary over several orders of magnitude between relative density values of 0% to 100%. *In situ* relative density of lunar soil has been found to be about 65% (medium to dense) in the top 150 mm, increasing to more than 90% (very dense) below a depth of 300 mm. These relative densities are very high when compared to a relative density of 65-75% which is the practical limit for field compaction of terrestrial soils. This high relative density of lunar soils was probably caused by the shaking effects of shock waves generated by innumerable meteoroid impacts.

Compressibility

Compressibility describes the volume change that occurs when a confining stress is applied to soil. It is quantified by the compression index, the decrease in void ratio that occurs when the stress is increased by an order of magnitude. The compression of lunar soils, measured in a vacuum, has been found to vary from 0.01 to 0.11, depending on the initial density and the applied stress. The compressibility curves for soils of different initial densities converge when the stress exceeds 100 kPa, which corresponds, on the Moon, to a depth of more than 30 m below the lunar surface.

Shear Strength

The shear strength consists of two components, a cohesive component, that is independent of the applied stress, and a frictional component that is directly proportional to the normal stress. Based upon a variety of data the following estimates for these components have been derived:

Cohesion = 0.1 to 1 kPa
Friction angle = $30°$ to $50°$

The higher shear-strength parameters correspond to higher values of relative density of the lunar soil. These values are relatively high, probably due to the interlocking of irregular and re-entrant soil particles under the low stresses present near the lunar surface. These values are thought to be useful for near-surface lunar structure and construction activities, but for heavy structures or deep excavations, a more complete study of lunar soil shear strength should be made.

Permeability and Diffusivity

The coefficients of permeability and diffusivity are used to evaluate the movement of fluid through a porous medium, and no direct measurements of these parameters have been made on lunar soil. Based on a test firing of the Surveyor 5 vernier engine on the lunar surface, the permeability of the soil to a depth of 250 mm was estimated to be 1 to $7 \times 10^{-12} \text{ m}^2$. Diffusion rates for noble gases

through lunar soil have been measured in the laboratory yielding values of 7700, 2300, and 1800 mm^2 s^{-1} for He, Ar, and Kr, respectively.

Bearing Capacity, Slope Stability and Trafficability

These three parameters control important engineering properties of the regolith. The ultimate bearing capacity defines the maximum possible load that can be applied without causing gross failure, and has been determined to be approximately 6,000 kPa for a one-meter footing on the lunar surface. The allowable bearing capacity defines a lesser load that can be applied without exceeding a given amount of settlement. For a maximum settlement of 10 mm for a load with a footing of less than 500 mm, data from the depths of astronaut boot-prints indicate, that for a 95% confidence level, the allowable bearing capacity should not exceed 2 kPa.

The slope stability of lunar soil is expected to vary widely from naturally compacted material to excavated material. Calculations indicate that a vertical cut to 3 m could be make in naturally compacted lunar soil, and a slope of 60° could be maintained to a depth of about 10 m. In contrast, a pile of uncompacted excavated soil could be raised to height of 10 m at an angle of nearly 40°.

Trafficability is defined as the capacity of a soil to support a vehicle and to provide sufficient traction for movement. From the experience of Apollo and Lunokhod missions, we know that almost any vehicle with round wheels will perform satisfactorily on the lunar surface provided that the ground contact pressure is no greater that about 7 to 10 kPa. The primary limitations on the trafficability of the lunar soil are speed and slope. The steepest slope that the Apollo Lunar Roving Vehicle could climb was 19° to 23°. Additional slope climbing capability could be attained by adding more aggressive tires to the vehicle. Particularly soft soil conditions were encountered by both Apollo and Lunokhod vehicles when approaching craters, particularly on the inside wall. Local problem areas may therefore exist for trafficability.

DIFFERENCES AMONG THE MODES OF FORMATION OF TERRESTRIAL AND LUNAR REGOLITHS

In order to understand the differences in physical properties among lunar and terrestrial regoliths one must first understand the basic differences in the modes of formation of these materials. Both regoliths are ultimately formed by breakdown of bedrock. Terrestrial regoliths are formed by a range of processes which commonly involve physical disintegration and some chemical change of the bedrock, transportation of the sediment so formed by wind, water or ice, commonly with additional physical and/or chemical modification, and redeposition of the sediment. These processes typically result in the production of a sediment which is relatively well-sorted both physically and chemically, and which is characterized by rounded particles. Sediments generally become smaller in grain size, more rounded, and more

chemically mature (stable in a hydrous environment at standard temperatures and pressures) as the distance of transportation from the bedrock source increases. The major exception to this generalization is erosion and direct deposition from ice which produces very poorly sorted sediments (grain sizes from rock flour to boulders), with little or no chemical change from the parent bedrock. The ice-transported sediments are rounded, however, and if ice melting occurs before sediment deposition, the sediments sizes are significantly sorted by transportation in the melt-waters. The sediments may then be further modified by soil formation, which causes further vertical physical and chemical differentiation and modification of the sediments and the addition of organic material to the upper regolith. The result is a regolith which is well-sorted with a primary vertical stratification typically modified by lateral facies changes.

In contrast, the lunar regolith is primarily the result of a single physical process, hypervelocity impacts (projectiles with impact velocities in excess of the speed of sound in the target material) of particles ranging in size from dust to small planets. These impacts cause major disintegration of the target material, typically forming angular fragments ranging in size from rock flour to large boulders, and transportation of these materials from the impact site is limited to ballistic projection of the fragments. Ballistic fragments with an initial velocity of greater than 2.4 km s^{-1} may be ejected from the Moon; particles with lower velocities are redeposited on the lunar surface, the larger particles forming *secondary craters*.

There is no sorting of particle size during ballistic transportation on the Moon as there is no significant atmosphere to cause differential hydrodynamic drag on particles of different sizes and shapes, as occurs on Earth. Chemical changes are limited to phase-transformations by high shock-pressures produced by impact, and changes in mineralogy associated with impact melting. These processes results in a suite of characteristic high-pressure minerals found only associated with impact structures. Impact melting results in a high proportion of rounded beads of glass in the lunar regolith, formed by ballistically projects melt droplets which rapidly solidify during flight to form amorphous glass beads before landing.

Although the result of repeated impacts is to continue to decrease grain size, reworking of the lunar regolith has not in general proceeded to a state of dynamic equilibrium in which the decrease in grain size due to impact fracturing is equal to the increase in grain size associated with melt solidification. The lunar regolith therefore consists of a poorly sorted aggregate of angular brecciated fragments and glass spherules. Layering in the regolith is associated with the overlap of ejecta blankets from different impact targets, and this layering tends to be modified by subsequent impact events (*gardening*). There is no lunar soil-forming processes equivalent to the hydro-chemical and organic processes of terrestrial soil formation. However, there is surficial regolith modification by exposure to the solar wind and micro-meteorite impacts.

DISCUSSION OF THE IMPLICATIONS OF REGOLITH PHYSICAL PROPERTIES FOR LUNAR BASE ACTIVITIES

From this preliminary review of the physical properties of the lunar regolith, I have identified two areas of potential concern for lunar base activities. These areas concern the probability of encountering cobbles and boulder in the regolith subsurface, and "dust" and heterogeneity in the fine fraction of the regolith.

Most of the published discussions on particle-size distributions are based upon data only from sieved samples of fines (<1 mm) or the coarse and fine fraction (<10 mm), ignoring the "lumps" (>10 mm) in the regolith. Coarse fragments of the regolith samples were hand-picked from the samples in the Receiving Laboratory and given their own numbers - one may therefore be able to reconstruct the original sample particle-size constitution, but apparently these data are not readily available at present. There is also the problem that meter-sized boulders were not sampled *en masse* for obvious practical reasons, so this particle size is completely missing from the sample analyses. Photo-geologic studies have been made of the larger boulder distributions, and more work is needed on this topic. In a conservative approach, we may not ignore the possibility of excavating large boulders even in the marie regolith distant from large, young impacts. Cobbles and boulders are visible on many of the lunar surface photographs, and if similar conditions exist in the subsurface, this large-size component of the regolith could cause engineering hazards.

Problems of "dust" from the lunar regolith have been briefly discussed by a number of authors (*e.g.*, *(1)*). There appear to be inconsistencies in some of these reports, however. Although there are many references to "dust permeating the samples" and "how quickly things were made dirty" in the astronaut voice communications of the Apollo lunar surface activities, the rock samples that were returned to the Lunar Receiving Laboratory at the Johnson Space Center were considered to be covered in dust only to the extent that would be expected from the packing of friable samples and transportation back to Earth (Don Morrison, personal communication, 1990). Some appearance of dusty-surfaces could have been the effects of darkening by exposure. The magnitude of the problems of dust associated with lunar surface activities remains unresolved at present. The main dust problems associated with lunar surface activities appear to be associated with porous surfaces, such as the space suits, or charged surfaces, camera lenses and other insulators. Other materials may still be mantled in dust by activities which cause ballistic disturbances of the regolith, but there is no evidence dust jumps onto all exposed surfaces. This dust may still be a major problem, and more study of this problem is required before extensive lunar surface activities are planned.

I am also concerned that not enough attention has been given to heterogeneity in particle-size in the fines. There is considerable variability in the mean grain size of the <1 mm fraction (41-123 microns), and I suspect that this variation may result in variations in physical properties that are being homogenized in the averages which are quoted. For example, I suspect that the significance of re-entrant surfaces

becomes less as the particle size decreases, which could have measurable effects upon soil cohesiveness and related properties. This topic should be studied in greater detail.

RECOMMENDATION FOR SITE-SURVEYS

Available data indicate that there is significant lateral heterogeneity in the lunar regolith. This heterogeneity exists both with respect to small-size particle distributions (<1 mm), which may affect bulk material properties, and with respect to the random distribution of large-sized particles (>100 mm), which need to be considered for mining and excavation operations. Vertical layering of the regolith is expected at most sites, and considerable vertical heterogeneity may also be expected. Detailed site-specific surveys are recommended at all sites where mining and excavation operations are planned. These surveys should include sub-surface profiling to determine the density and distribution of large, consolidated particles. This profiling should also determine the degree of subsurface layering. Core samples will be required to determine small-sized particle properties if significant layering is recorded.

These surveys would be desirable, and perhaps essential for engineering purposes if the boulder problem is thought to be significant. They would be desirable for geophysical studies under any circumstances, primarily because the rapid change in physical properties of the upper regolith with depth (increase in compaction, etc.). Lateral variations in regolith thickness may cause significant uncertainties in local corrections for regional/global measurements, as in static corrections for seismic data, shallow refraction and conductor corrections for heat flow and electrical data, etc. For engineering considerations, a high resolution survey with a penetration of about 10 m would be desirable. For geophysical site surveys a lower resolution with greater penetration, of the order a km should suffice. Ideally these surveys should give some three-dimensional resolution of subsurface structure without the need for a dense two-dimensional grid of surface profiles. Technology analogous to side-scan sonar or imaging radar would be useful in this respect.

There are three likely candidates for site-survey geophysical methods, active seismic, electrical or electromagnetic techniques. The magnetic contrast among boulders and regolith, and bedrock/consolidated regolith/regolith without a strong inducing field is likely to be insufficient to produce a useful magnetic signal. Similarly, gravity anomalies associated with long-wavelength, shallow density contrasts or small, shallow density contrasts are unlikely to be resolvable from instrumental noise and deeper source anomalies. Electrical methods could probably be devised with sufficient sensitivity to locate shallow buried boulders, but these techniques would probably require interpretation from an electrical section of the regolith to a structural section. Direct imaging techniques such as reflection seismic or radar techniques would probably have the best resolution for this problem and could be most easily adapted to profile sweeps in a lunar environment.

Both radar and seismic methods have been successful in revealing layering in the lunar regolith. Under the high vacuum conditions of the lunar surface, difficulties may be encountered in coupling a seismic source and receivers to the regolith without stopping the rover and "planting" both source and receivers for each profiling point. Thus, radar probably offers the most attractive option for shallow "rover profiling" with a sideways scanning radar system mounted perpendicular to the rover traverse direction.

Trafficability appears to be primarily restricted by surface topographic features, although problems of raising the loose surface regolith must be considered. These problems appear to be associated with ballistic trajectories associated with surface activities which disturb the surface, and with electrostatic attraction by the lighter particles to charged surfaces.

TERRESTRIAL ANALOGUES

No terrestrial analogue adequately covers the range of properties likely to be experienced in the lunar regolith, but analogues for different physical and mechanical properties may be found. Dry desert conditions in which eolian sands and fluvial gravels are interfingered may present a useful analogue for the lunar regolith for tests of subsurface profiling, both for the detection of boulders and to identify subsurface layering. The properties of the lunar regolith dominated by the fine-sized fraction of the regolith are unlikely to be reasonably represented by any terrestrial regolith materials, primarily due to the different modes of formation of the terrestrial and lunar regoliths. These lunar regolith properties may by simulated by suitably crushed basalt, mixed perhaps mixed with a fine silt component to simulate the effects of the glass component in the lunar regolith.

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