Simulating the Effects of Gravitational Field and Atmosphere on Behavior of Granular Media

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Designs for structures, vehicles, and equipment to be used on the surfaces of the moon and Mars cannot be optimized without a knowledge of how soils in various gravitational fields and atmospheric conditions behave when subjected to static and dynamic loading. Strengths of the lunar and Martian gravitational fields (0.17 and 0.38 times terrestrial, respectively) can be simulated for approximately 30 sec by flying the KC-135 aircraft through appropriate parabolas. Effects of gravitational field on explosion crater formation and projectile penetration have been investigated. Techniques devised for use in these tests are discussed. Diameters of explosion craters and depths of projectile penetration in sand were found to increase as the gravitational field strength decreased. Atmospheric pressure variations down to ultra-high vacuum are significant in the behavior of rock powders. Approaches used in ultra-high vacuum tests on adhesion and compressibility of basalt powders are discussed. The forces of adhesion between rock powders and metal alloy surfaces were noted to be greater in ultra-high vacuum than in air. The forces required to compress slowly a basalt powder are greater after bakeout and exposure to ultra-high vacuum than when this rock powder is tested at atmospheric pressure.

Introduction

KNOWN to exist on terrestrial and lunar[1,2] surfaces and probably also to be found on the surfaces of Mars,[3] Mercury, and Venus are fragments of rocks and minerals referred to as granular media or soil. Success in optimizing designs of landers, shelters, roving vehicles, and foundations for astronomical observatories will depend to a considerable degree upon accurate knowledge of the behavior of such media.[4] A long-term goal should be acquiring a knowledge of the load-displacement-temperature-time relationships for granular media existing on planetary surfaces.

Granular media are composed of discrete grains derived from rock and subsequently transformed and transported by weathering, erosion, mass wasting, meteoroid impact, volcanism, and seismic activity. Their engineering properties are complex functions of mineralogical composition, amount and composition of absorbed fluids, of fluids and gases present in voids, sizes and shapes of particles, and relative bulk density.

Soil particles on the lunar surface may be relatively free of adsorbed gases because of the low atmospheric pressure and the effects of solar radiation. Water in soil pores can probably be ruled out near the surface but it has been suggested that ice may exist at depth.[5] Little is known of Martian soils. Discussion of problems of simulating the environments of Venus and Mercury and the atmosphere of Mars is beyond the scope of this paper.

So far, only limited in situ tests have been performed on lunar soils and none on Martian soils. Hence, laboratory tests of simulated lunar and Martian soils with appropriate environmental simulation are likely to be important.

Use of the Terzaghi bearing capacity formula[6] permits an estimate to be made of the effect of varying gravitational field strength on bearing capacity for relatively dense and incompressible soils. Although some approximations are involved in this bearing capacity formulation, there is experimental evidence that it gives a valid estimate where relatively dense soils are involved.[7-9] For relatively dense cohesionless sands, bearing capacity appears to be directly proportional to gravity. For relatively loose and compressible soils there is less certainty with regard to gravitational effects on bearing capacity. Some pioneering experimental and analytical work has been done on soils of this type by Halajian and his coworkers.[7] The bearing capacity of loose and compressible rock powders exhibiting appreciable cohesion is much less sensitive to variations in gravity than is the bearing capacity of cohesionless sand. The subject of the gravitational field dependence of soil bearing capacity deserves additional study.

The gravitational field dependence of low-velocity projectile penetration and rate of penetration into soils is even less amenable to an analytical approach than is bearing capacity. Depths and diameters of explosion craters are also not readily predicted as a function of gravitational field. Dynamic penetrometers[10-12] may be applied to remotely controlled determination of the properties of planetary soils. Explosives may be used as seismic sources in active seismic experiments and as an aid in excavation on the moon and Mars. In the absence of generally accepted theoretical approaches for calculating the gravitational field dependence of significant parameters for penetration and cratering events in soils, experiments to determine dependence become particu-

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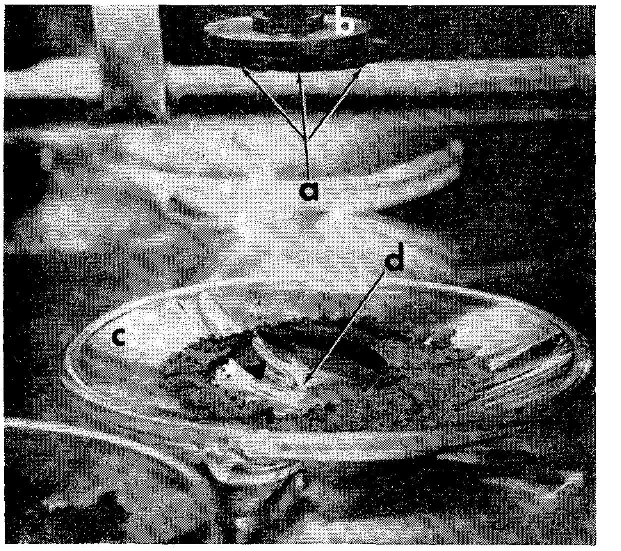

Fig. 1 Basalt powder (a) adhering to 2024 aluminum disk (b) in vacuum of 1×10^{-10} torr.[13] Also shown is the watch glass (c) from which the adhering powder was cleanly removed (d). The aluminum disk (b) is 0.32 cm thick and 3 cm in diameter. Attainment of 1×10^{-10} torr was possible after a bakeout of 250°C for 24 hr.

larly desirable. Techniques and results for some such experiments are presented in this paper.

Simulation of atmospheric effects on behavior of granular media has been investigated at the Air Force Institute of Technology (AFIT) for three problems: adhesion to metals in ultra-high vacuum, variation of soil compressibility with atmospheric pressure, and variation of explosion crater depths and diameters with atmospheric pressure. Only the first two problem areas will be discussed in this paper.

It has been noted that rock powders on the lunar surface will adhere to the surfaces of landing spacecraft[1] and boots of men.[2] More work is needed to examine the significant parameters governing the phenomena of adhesion. In our experiments,[13] forces of adhesion up to 495 dynes/cm^2 between soils of basaltic composition and 304 stainless steel and 2024 T-4 aluminum were measured in a 10^{-10} torr vacuum. An example of the adhesion noted is shown in Fig. 1. The results of this earlier investigation led to more recent work discussed in this paper on compressibility of the basalt powders as a function of atmospheric pressure. In the very low atmospheric pressures found on the moon, the frictional forces and forces of attraction between individual particles in a soil mass will be greater than in the terrestrial atmosphere thereby reducing the settlement resulting when such a soil mass is subjected to load.

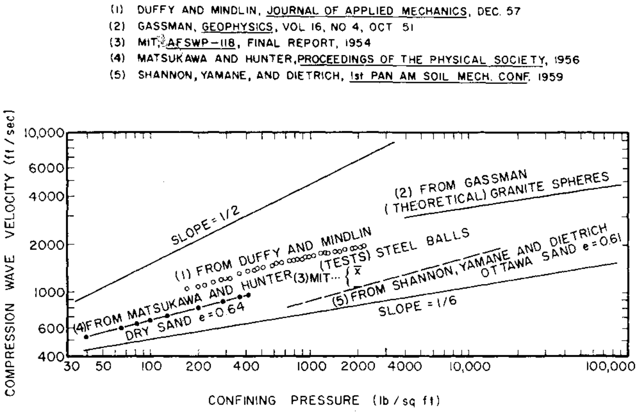

Fig. 2 Compression wave velocity vs confining pressure for granular media—modified from Richart.[22]

Completeness of simulations in problems of extraterrestrial soil mechanics would require that samples of the appropriate rock be available and that soils for experiments be derived from that rock by soil-forming mechanisms such as, for example, hypervelocity impact. Such materials then would be subjected to appropriate weathering in the presence of the atmospheric and solar radiation conditions simulating those existing on the planet whose soils are to be investigated. In the case of simulation of lunar soils, comminuted rock should be subjected to simulated solar radiation and thermal cycling in the presence of vacuum. Soils so treated should be tested at 10^{-10} torr or below in a gravity field 0.17 times terrestrial. Completeness of simulation has generally not been achieved in soil mechanics work to date. Simulating lunar gravity and atmospheric conditions simultaneously would present great problems to the experimenter.

Experiments at AFIT have considered gravity and atmospheric pressure effects separately. In addition, no attempt has been made to subject soils to effects of hypervelocity impact and to simulated solar radiation before tests. Effects of shock[14] and irradiation[15,16] on the formation and behavior of lunar soils may be difficult to duplicate in the terrestrial laboratory but could alter the engineering properties. Experiments which involve determining effects of ultra-high vacuum and gravity field separately are therefore based on the assumption that first-order effects of these two facets of the lunar environment can be studied independently of effects of shock metamorphism resulting from meteoroid impact, solar radiation, and unknown processes of internal origin[17] (i.e., the migration of volatiles from below the lunar surface).

Simulating Effects of Gravitational Field

Forces on volume elements in a mass of soil consist of both body forces and surface forces. The magnitude of surface forces is proportional to the surface area or to the square of a characteristic linear dimension D of the volume element. The magnitude of the body force is proportional to volume or to the cube of the linear dimension D. The ratio of body forces to surface forces on a volume element is, therefore, proportional to D. Fine-grained soils have much greater surface area per unit volume of solids than do coarse-grained soils. Surface forces will predominate in the fine fractions of granular media and body forces will be dominant in the coarser fractions.[6,18] In the terrestrial environment, the behavior of the coarse-grained soils (as sands and gravels) is influenced by body forces to a much greater degree than fine-grained soils with silt-sized and clay-sized particles.[18] Scott[19] has noted that the gravitational body forces may become important in the lunar environment for grains larger than 0.1 mm to 1.0 mm in diameter.

Gravitational field strength is important in determining the pressure of confinement on a volume element in a given granular media at given depth. Confining pressure, which is directly proportional to g, influences the value of p in the soil mechanics Coulomb equation[6] $s = c + p \tan\phi$. In this equation, s is the shearing strength or resistance to shear on a plane in the soil mass upon which failure is imminent, p is the effective normal stress on that plane, ϕ is the angle of internal friction of the medium and c is the cohesion (shear strength when p is 0). Shear strength is a function of gravitational field for soils where ϕ is not zero.

The compression and shear wave velocities in a granular medium of given porosity and at given depth are also functions of confining pressure[20-23] (e.g., Fig. 2) and therefore of gravitational field.

Techniques for Simulating Gravitational Fields

The simulation on earth of the gravitational body force acting on soil on another planet can be accomplished by using a soil of different particle density, by submerging the soil in a fluid of appropriate density, or by placing the soil on an accelerated platform. The first two methods present difficulties because they may cause soil parameters c and ϕ to change in an unwanted manner. In tests involving dynamic loading, the first method will lead to distortions in the model that may be unacceptable. Dynamic loading of the soil with pore fluid would probably lead to pore pressures at unacceptable levels, which might make test results impossible to interpret.

The accelerated platform might be located on a centrifuge, in a vertical shaft, or be the floor of an aircraft flying appropriate parabolic maneuvers. We know of no reports of experiments on granular media being conducted in a centrifuge. The so-called Coriolis acceleration would present problems for such tests. Some experiments with granular media on accelerated platforms have been reported.[24] Several other investigators have reported using aircraft to simulate gravitational fields in soil mechanics experiments.[8,9,25–27]

In 1958 the Air Force modified a standard C-131B to perform zero-g maneuvers. Responsibility for the aircraft and all Department of Defense (DOD) zero-g testing was given to the Deputy for Flight Test of the Aeronautical Systems Division (ASD), Air Force Systems Command, at Wright-Patterson Air Force Base, Ohio. Initially, the cabin size of the C-131B and its zero-g time of 15 sec per maneuver were adequate to satisfy needs of test programs. However, requirements outgrew the capability of the C-131B. It was decided to modify a KC-135A for zero-g testing (30 sec) and to keep the C-131B as a backup aircraft. The first zero-g KC-135A began test flights in 1960 and was soon involved in training astronauts for the National Aeronautics and Space Administration (NASA) Mercury Program. Since that time thousands of maneuvers for DOD and NASA sponsored experiments have been flown. Approximately 95% of them are flown to simulate zero-g. The other maneuvers have simulated lunar (0.17 g) and Martian (0.38 g) gravity as well as 2.0 g and 2.5 g. Soil mechanics experiments have been flown on only a small percentage of the flights and usually as not the only experiment being flown.

Design of the Experiments

The size of the experimental equipment is limited by the capacity of the aircraft's fuselage. The KC-135A aircraft operated by ASD will not accommodate equipment taller than 78 in. nor wider than about 110 in. Experiments involving dynamic loading are therefore limited by the amount of soil necessary to negate boundary effects, and they must be enclosed, so that displaced soil particles cannot enter critical aircraft components and cause a safety hazard. Safety considerations also restrict the energy and momentum of explosives and impacting projectiles used in such experiments.

The choice of a soil for use in experiments is critical. Vibrations are present which will tend to compact the soil. This is undesirable in tests such as ours where reproducibility of results has been required. Therefore, a soil has been chosen that will readily attain a relatively dense state and can thus be kept at a controlled void ratio. There is little room or time to perform involved sample-preparation tasks aboard the aircraft, so the sample medium had to be one that would not be greatly altered by repeated performances of the test. Water content is difficult to control but may have a strong effect on results. For AFIT experiments in the ASD aircraft, the medium used has been Ottawa Sand.[28] This is a uniform, air-dry silica sand with the grain shape and size distribution of Fig. 3. In this medium gravitational or body forces are dominant ($\phi > 0$) and the forces of interparticle cohesion (which are independent of gravity field) are negligible ($c = 0$). Experimentation with this medium should give an upper bound on gravity effects for granular media.

Since the aircraft cannot maintain the desired gravity levels for more than about 30 sec, the experiment must be one for which this length of time is enough for acquisition of at least one piece of data. The aircraft can fly gravity simulation maneuvers in close succession, but certain preparations are normally necessary before the experiment can be repeated. These preparations should be carefully preplanned and practiced.

The parabolic maneuvers cause discomfort to experimenters not accustomed to a varying gravitational field, and even people with experience cannot perform with the usual concentration, speed, and dexterity. Data gathering must be as automated as possible. Photographic records of events are needed which may be used in checking the data taken in flight or as the primary source of data if necessary.

Power availability must be considered in the choice of experimental equipment. The KC-135A flown by ASD has available 28-v dc, and 110-v, 400 cycle, single-phase and 3-phase ac power. Bottles of compressed gasses can be brought aboard.

The gravity level attained can be monitored in a number of ways. Usually, the pilot informs the experimenters when

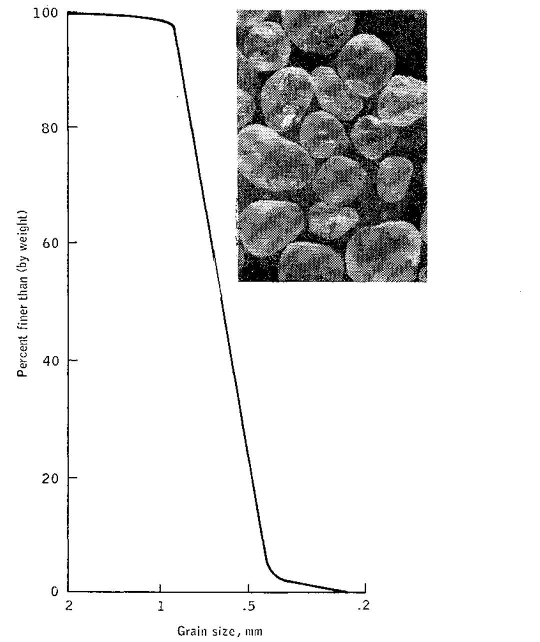

Fig. 3 Grains of Ottawa sand magnified, and grain size distribution.

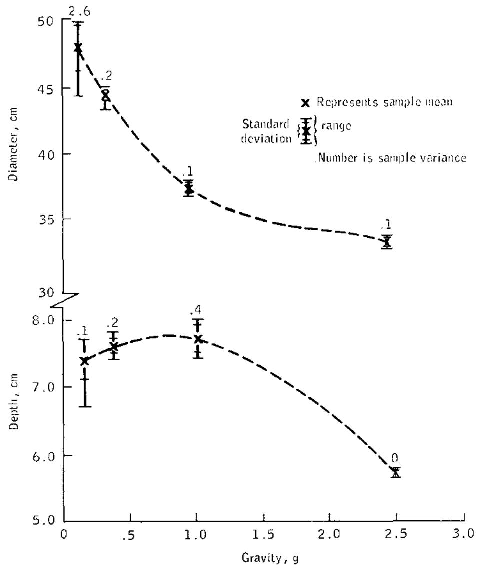

Fig. 4 Explosion crater diameter (lip-crest-to-lip-crest) and apparent depth vs gravitational field for cap and primacord.[26]

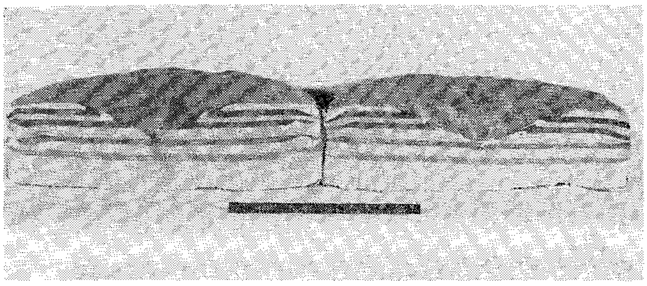

Fig. 5 Profiles of craters formed at 2.5 g (left) and 0.17 g (right) in sand with colored layers.[26] The major units of the scale are inches. There is an apparent slumping of layers in the 0.17 g crater.

the desired gravity value has been reached, and the accepted error is taken to be $\pm$ 0.01 g. A g-meter can, however, be placed in the field of the camera being used in the experiments. Another method is to record the output of accelerometers aboard the aircraft.

Experiments and Results

One series of experiments performed at AFIT in the ASD aircraft involved the firing of small explosive charges in Ottawa sand to form craters in gravitational fields of 0.17, 0.38, 1.0 and 2.5 g.[26] Explosion crater depths and diameters were measured. The results of some of the tests are shown in Figs. 4 and 5. Crater diameter and depth vary significantly as gravitational field changes.

In another series of tests,[27] cylindrical metal projectiles were fired at low velocity into a bed of Ottawa sand. Maximum penetration and time to complete penetration were found to vary significantly with gravity field strength as shown in Table 1.

Simulating Effects of Atmosphere

All work done so far in this area at AFIT involves simulation of the vacuum found on the lunar surface rather than atmospheres of Mars or other planets. The effect of vacuum on the properties of granular media is significant[29–45]; however, the absolute magnitude of this effect for particular cases is as yet unpredictable because of a number of problems associated with testing granular media in vacuum. Two of these problems are 1) the difficulty in obtaining and analyzing relatively clean surfaces on individual soil particles within a mass of particles in ultra-high vacuum and 2) the problem of designing experiments for ultra-high vacuum.

Surface Cleanliness

The degree of surface cleanliness of the individual soil grains is an extremely important parameter in determining the response of a soil mass which is loaded or contacted.[42] Because soil particles in the terrestrial environment are encased within an adsorbed film of gases and moisture, they are seldom in direct contact. Instead, the adsorbed film of one grain contacts that of another. This results in large separation distances on the atomic scale and consequently the dominant interparticle forces are the long range Van der Waals forces.[43] If the surfaces of the soil grains are cleaned, then the grains come into closer contact, resulting in stronger Van der Waals forces and possibly some atomic bonding if the surfaces are clean enough and the separation distances are small enough.[42] In addition, the coefficient of friction between the soil grains is increased, and a larger force is required to move one grain relative to another.[34,35] These two phenomena can measurably affect the load-deformation relationships of a soil mass. Relating change in behavior of the soil mass to change in surface cleanliness would be a way to a true understanding of the phenomena. Without some knowledge of the degree of cleanliness for simulation tests, conclusions from such tests are of necessity general and imprecise.

To determine the degree of surface cleanliness adequately, the experimenter needs to know the thickness and chemical composition of the adsorbed surface film before and after exposure to the vacuum environment. The nature of the adsorbed film is such that this determination is difficult. If the experimenter could be assured that he had stripped away the entire surface film, then he could be assured of 100% cleanliness. The volume of the gases stripped away from a soil grain can be determined, but the authors know of no technique to use in determining the amount of adsorbed film remaining on grains of soil inside a soil mass in an ultra-high vacuum. A method used to determine the volume of the gases lost by the particle, which has been used by several investigators, is the same technique used to determine the chemical composition of the adsorbed film. A partial pressure gauge operative during the various stages of pumpdown determines the partial pressure of the gases in the system at these times. Assuming that all of the gas in the system is derived from the adsorbed surface film on the grains, the volume of gas liberated can be computed given the pumping speed of the system. A discussion of this technique is given by Vey and Nelson.[44] It is very difficult to make a satisfactory error analysis for results obtained using this technique.

In recent experiments[45] conducted at AFIT the technique resorted to was the one usually used in experiments with granular media in ultra-high vacuum—employ a standard procedure to insure that the degree of surface cleanliness is increased but not be concerned with measuring cleanliness. A common misconception is that the vacuum level of the experiment is a measure of the degree of surface cleanliness. This is not true.[36] In experiments on the compressibility of rock powders,[45] tests were performed at atmospheric pressure, at 10^{-8} torr, and 10^{-10} torr. The nature of the system was such that the 10^{-8} torr tests were performed without prior bakeout, but the 10^{-10} torr tests involved a system bakeout at 200°C for 18 hr and a superimposed bakeout of the soil sample by a small adjacent heating coil at 300°C for 3 hr. This exposure to these high temperatures was intended to increase the degree of surface cleanliness of the soil grains. The results of these tests differed radically; however, one run scheduled for 10^{-10} torr developed a leak sometime during pumpdown and after exposure of the sample to the bakeout the vacuum level attained was in the 10^{-8} torr range at the time of test. The results of this test were nearly the same as the 10^{-10} torr results and not at all like the usual 10^{-8} torr test results. The importance of this observation is that the vacuum level does not necessarily determine the degree of surface cleanliness. Until better, more precise, and more easily implemented techniques are developed to measure the degree of surface cleanliness of the particles, the results of soil tests in ultra-high vacuum will disclose only general trends, and a true understanding of the phenomena will not be achieved.

Table 1 Variation of maximum projectile penetration and time to complete penetration with change in gravitational field[27a]

Gravity	Number of shots	Maximum penetration Range, cm	Maximum penetration Mean, cm	Standard deviation, cm	Mean of time to complete penetration, msec
1.00 g	6	12.4–16.0	14.6	1.5	24.70
0.38 g	10	15.5–16.7	15.9	0.3	27.99
0.17 g	8	17.7–19.3	18.6	0.5	32.78

[a] Average impact velocity was 1300 cm/sec. The flat-nosed cylindrical aluminum projectile was 1.27 cm in diameter and 33 cm long. It weighed 64.1 gm and impacted in Ottawa sand in a cubical container 61 cm on each side.

Design of the Experimental Apparatus

In the Introduction, the importance to soil mechanics of in situ and laboratory tests was alluded to. Unfortunately this fact does not imply tests commonly used are either a measure of fundamental soil properties or are easily adaptable for use in ultra-high vacuum. Indeed there are problems in defining what the properties are that should be measured. One property of particular interest, as was mentioned in the Introduction, is the property of compressibility.

In the previously mentioned series of experiments at 740 mm Hg and in vacuums of 10^{-8} torr (without bakeout) and 10^{-10} torr (with bakeout) we investigated the compressibility of a simulated lunar soil. The granular medium used in the simulation was the comminuted tholeiitic basalt rock (from near Madras, Oregon)[13,46,47] that passes the U.S. Standard Number 250 sieve. The composition of this rock was thought to be similar to the soil found on the lunar surface.[48] The grain size distribution as determined for this medium by hydrometer analysis is shown in Fig. 6 along with a photomicrograph of some typical particles. With this rock powder, interparticle forces, which are dependent on atmosphere, will be significant in determining behavior. Soil compressibility[49–51] may be calculated from the results of a soil mechanics test often referred to as the one-dimensional compression test. The test might be more aptly termed a one-dimensional strain test because the cylindrical soil sample, often one inch thick and four inches in diameter nominally, is confined within an essentially rigid ring while it is loaded parallel to the axis of the sample. The circular loading plate is nearly four inches in diameter so that soil is not permitted to flow out between the edge of the load plate and the confining ring.

As the test progresses, the pressure exerted by the loading plate is increased by increments and a plot is made of void ratio e vs pressure p. From the e–p plot, compressibility parameters may be calculated.[6] In order to perform this test in the vacuum chamber, it was necessary to modify the configuration of the test apparatus. To reduce the volume of soil and hence, the outgassing problems, the diameter of the ring was reduced to 1 in., and the depth to 0.7 inch. Also to facilitate outgassing, narrow vertical slits were cut in the sides of the ring. The loading plate used was designed with a diameter of 0.8 in., so that contact between the metal ring and the metal loading plate, which would pose frictional and cold welding problems in ultra-high vacuum, would be eliminated.

Experiment and Results

For our experiment it was necessary to avoid vibrating the soil samples in the vacuum chamber during bakeout and pumpdown. Our vacuum system[13] meets this requirement for an essentially vibration free environment because there are no mechanical pumps or other vibration producing elements in or near the system. The system has five sorption pumps for rough pumping, a titanium sublimation pump, and a 500 liter/sec ion pump.

Rate of loading is important in compressibility tests on rock powders. In order to avoid unwanted pore pressure effects the load application was controlled so that the loading plate moved at approximately 0.005 in./min for all tests.

Some of our results are shown in Fig. 7. Both the in-air and in-vacuum tests were performed on the chamber apparatus. These results, although they must be viewed as qualitative, do demonstrate that the compressibility of the basalt powder is less for the samples exposed to bakeout and pumpdown to 10^{-10} torr than for similar samples tested at atmospheric pressure. Much remains to be learned about the compressibility of rock powders. More experiments should be performed in the future to establish the effect of composition, grain size, and length of time exposed to bakeout and vacuum on compressibility. Tests should be performed that involve exposure of the powders to bakeout and testing in air as well as bakeout and testing in vacuum. The effects of several cycles of bakeout in vacuum and exposure to air or nitrogen should be examined.

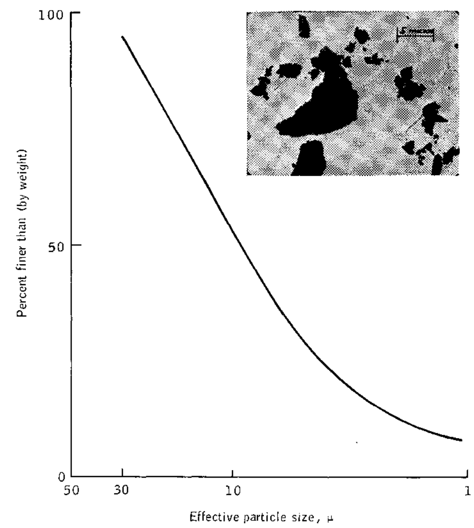

Fig. 6 Grains of comminuted basalt rock magnified, and grain size distribution.[13,45]

Future Role of Simulation

Knowledge of the behavior of granular media on planetary surfaces is needed. Approaches to obtaining that knowledge include simulation, in situ testing, analysis, and extrapolation from terrestrial soil mechanics. Given the primitive state of analysis applied to granular media and the often questionable nature of extrapolation, it is apparent that much dependence must be placed on simulation and in situ testing. In situ testing (on planetary surfaces) is preferred and opportunities for such testing should be capitalized on to the fullest extent. The Luna 13 penetrometer, the Surveyor surface sampler, and the Apollo astronauts performed the first in situ soil mechanics tests on the moon. In situ tests will continue. They will furnish incomplete data under present expectations.

Considerable reliance must be placed on simulation to complement and assist in interpreting in situ tests. Three classes of materials may be used in simulation: returned lunar samples, simulated lunar materials, and idealized media. Tests on simulated lunar materials are potentially useful in two ways. They may furnish data of value in themselves and they will assist in the development of techniques for testing returned lunar samples. An example of the use of an idealized media in simulation is the application made of Ottawa sand to furnish a bound on gravitational field dependence of the low velocity impact and explosion cratering events. Comparison of results of soil mechanics experiments on simu-

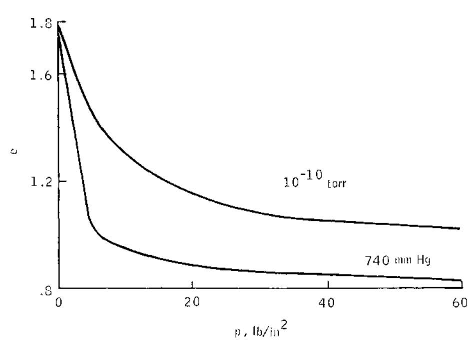

Fig. 7 Void ratio (e) vs pressure (p) curves for starting void ratio of approximately 1.75.[45] Void ratio is defined as volume of voids divided by volume of solids in a given volume of soil.

ated lunar soils and returned lunar soil samples, both in a simulated lunar environment, may lead to some interesting results relating directly to the nature of interparticle forces and indirectly to effects on silicates of solar irradiation, shock, and internal processes found on the moon.

Tests on returned lunar samples could, however, be misleading as a guide to the behavior of granular media on the lunar surface because of the disturbance and change in soil particle arrangement during collection and transport from the moon.

There is a possibility that granular media returned to terrestrial laboratories for study will be significantly disturbed by forces imposed while entering the Earth's atmosphere and subsequent handling even in the finest vacuum systems. A large, manned, Earth-orbiting space station has been proposed. Consideration should be given to the establishment in such a station of the capability for the performance of ultra-high vacuum, thermal and solar radiation effects experiments on granular media from earth, from the moon, and eventually from Mars.

Whether future investigations of the properties of extraterrestrial soils are conducted in earth orbit or in terrestrial laboratories, the use of such soils as an extraterrestrial resource to be used on the moon and planets should also be considered. Many questions relating to the nature of granular media on planetary surfaces must be answered by studies involving simulation before extraterrestrial bases can be established.[52] Increasing knowledge of how soils behave in extraterrestrial gravitational fields and atmospheric environments can contribute to an improved understanding of the basic phenomenology underlying soil behavior in the terrestrial environment particularly with reference to effects of gravitational body forces and soil particle surface forces in determining soil behavior under various loading conditions.

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Revised Lunar Surface Thermal Characteristics Obtained from the Surveyor V Spacecraft

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Higher lunar surface temperatures have been obtained from Surveyor data than from Earth-based telescope measurements. In addition, temperatures derived from different sensors located on the Surveyor spacecraft were not entirely compatible. This paper presents the results of error analyses on the Surveyor V thermal data. In the compartments, heat conducted from the other faces is significant and is included in the latest calculations. Derived postsunset temperatures from solar panel data have total errors similar to those from the compartment thermal-sensor data. The actual temperature-sensor measurement inaccuracies, uncertainties in view factors, and conduction effects are the most significant sources of error. Other sources are uncertainties in internal heat loss, solar absorptance, and emissivity. Error bands for these factors are described. The overlapping of these error bands with each other and with the Earth-based results illustrates the degree of agreement of the data from the different sources. For postsunset, Surveyor V data previously had inferred a thermal parameter (γ), of about 400, whereas Earth-based measurements indicated $\gamma \simeq 850$. The latest compartment-based γ from Surveyor V is near 600 and from solar panel data it is near 1000.

Nomenclature

C = mc_p/A = heat capacity coefficient, w-hr/°K-m^2
F_{ij} = view factor from surface i to surface j
K = kA_c/LA_i = conductivity coefficient, w/°K-m^2
$\dot{q}$ = conduction heat flux from inside of the compartment to the outboard face = 3.5 w/m^2
S = solar radiation = 1375 w/m^2
T = temperature, °K
α_s = solar absorptance
$\alpha',\beta',\gamma',\delta'$ = orientation angles
β = angle between direction of sun and normal to panel
γ = $(k\rho c)^{-1/2}$, cm^2 sec$^{1/2}$ °K/gm-cal
ϵ = emittance
σ = Stefan-Boltzmann constant = 5.675×10^{-8} w/m^2-°K
ρ_l = lunar albedo, lunar reflectance to solar irradiation = 0.077 (Earth-based)
ϕ = sun elevation angle above lunar horizon, deg

Subscripts

0 = compartment surface containing thermal sensor (inorganic white); $\alpha_{0s} = 0.20$, $\epsilon_0 = 0.87$
1 = sunlit lunar surface; $\epsilon_1 = 1$ (brightness assumption)
1′ = shaded lunar surface
2,3 = vertical sides of compartment (inorganic white)
4 = inboard surface (polished aluminum); $\alpha_{4s} = 0.10$, $\epsilon_4 = 0.04$
5 = bottom (polished aluminum)

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