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MECHANICAL, OPTICAL, THERMAL AND ELECTRICAL PROPERTIES OF THE SURVEYOR 1 LANDING SITE

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ABSTRACT

Surveyor 1 data are evaluated with particular emphasis on the soil mechanics of the landing site.

A downward revision of the bulk density of the lunar surface material from a previously suggested value of 1.5 g/cm3 to about 1 g/cm3 is proposed on the basis of mechanical, thermal, photometric and dielectric evidence. The revision indicates an underdense, partially consolidated material that can be approximated on earth by snow or semi-welded tuffs. The principles of conventional soil mechanics do not readily apply to the study of such materials.

Further analysis of Surveyor 1 data and, particularly, coordination between astronomical and on-site measurements of the lunar surface are suggested to refine these estimates and increase the usefulness of future Surveyors.

INTRODUCTION

Surveyor 1 was man's first successful attempt to physically touch and disturb the surface of an extraterrestrial body and procure strain gauge and photographic records of the event.

Despite the substantial scientific report (Ref. 1) released by the National Aeronautics and Space Administration within a remarkably short time after the historic landing, it is still too early to say whether we have derived all the intelligence we can about the nature of the lunar surface from these unique records. The need for and usefulness of future lunar missions, manned or unmanned, may well depend upon our ability to interpret astronomical and Surveyor-type data, and to single out key measurements and observations. Correlation of on-site and remotely measured lunar data could make the interpretation of these data less ambiguous.

Consequently, the purpose of this communication is: 1) To re-examine the Surveyor findings and estimate, in the light of recent research at Grumman, some key properties of lunar "soils" which were not directly measured by Surveyor; 2) To stress the importance of certain on-site and remote measurements of the lunar surface and the need to coordinate these measurements for more efficient, long-range exploration of the moon.

THE IMPORTANCE OF BULK DENSITY IN LUNAR DATA INTERPRETATION

Next to bearing strength, the key soil properties, in probable order of importance, are bulk density ρ, interparticle cohesion c, and friction angle ϕ. The interpretation of the Surveyor data is complicated by the fact that these parameters can combine in an infinite number of ways to describe a soil model that has the bearing strength of the landing site as recorded by the strain gauges. Furthermore, the term "bearing strength" is hard to define since it can be a function of dynamic effects, the gravity field, pad diameter, sinkage, etc. Whether these factors affect bearing strength depends primarily upon the porosity or bulk density* of the material. Independent measurement of bulk density by Surveyor would have considerably helped in estimating the soil parameters ρ, c and ϕ. However, it may be possible to extrapolate these, now a matter of judgement, from other aspects of the Surveyor data such as mode of soil failure, the apparent absence of loose dust on the moon and other lines of evidence discussed below.

The re-evaluation by this writer of the measurements and observations made by Surveyor 1 indicates that a reasonable case can be made for revising the preliminary estimates of soil parameters (Ref. 1) from a "terrestrial" type soil to a material less densely packed and more cohesive. The following are some of the reasons why an inquiry into the bulk density of the material disturbed by Surveyor 1 is important: 1) The principles of conventional soil mechanics may not readily apply to the study of lunar soils because the reduced bulk density emerging from the proposed revision falls outside the limits within which these principles are valid.

* Bulk density ρ and porosity p are related by the following expression:

$$p = 1 - \frac{\rho}{\rho_0}$$

where ρ_0 is the density of the material at zero porosity. In the discussions that follow a value of 2.75 g/cm^3 is assumed for ρ_0. This value is a reasonable average for most silicate minerals likely to be found on the moon.

2) Everything else being equal, a few percent revision of bulk density could affect the estimate of cohesion by as much as an order of magnitude. 3) Interpretation of present and future lunar photometric, polarimetric, radio-thermal and radar data depend largely upon a knowledge of bulk density, or porosity, of the undisturbed material.

A NEW LOOK AT LUNAR SOILS

A property of the lunar surface about which there appears to be a rare unanimity of opinion is the high porosity of the outermost layer of the moon. Estimates of this porosity run generally above 50%, depending upon the wavelength of the reflected or emitted energy that is being analyzed. (Earth soils rarely reach or exceed a porosity of 50%). The study of lunal soils should be approached in the broader context of the full spectrum of porous media that are likely to exist on the moon. These media include low-porosity soils whose properties and behavior are well understood, softer, highly porous powders which we will call "fluff", and harder, partially or fully consolidated, materials of any porosity which we will call "rock-froth", for lack of a better term. A porosity of 50% may be considered as a convenient demarcation line between "fluffs" and "soils". These particulate media are characterized by different modes of failure as illustrated in Figure 1.

The bearing strength vs porosity relationship of these three media are shown in Figure 2 based on analyses reported in Ref. 2. The semi-empirical curves in Figure 1 are described by the following expressions:

Soil $$f = S_g \rho D N_\rho \quad (1)$$

Fluff $$f = (N_s \frac{z}{D} + N_c) \cdot \frac{f(e)}{d} \quad (2)$$

Rock froth $$f = 1,400\ (1-p)^{2.6} \quad (3)$$

Where f is bearing capacity in kg/cm2; N_s and N_c are dimensionless constants which depend on porosity, p, as defined in Ref. 2; z and D are penetration and diameter of pad, respectively; f(e) is average surface energy of the particle system and d is particle diameter. The term f(e)/d represents interparticle cohesion expressed in dynes/cm2. In equation (1) S_g is a form factor; N_ρ is a constant which depends on the soil friction angle; ρ is bulk density. Note that ρ is a function of the gravity field.

Of the above three equations, only the first is familiar to students of soil mechanics. It applies only to cohesionless soils whose porosity is below 50%. The other two equations were recently derived at Grumman. Equation (2) expresses the bearing strength of soils whose porosity is above 50%. It agrees quite well with test data in the literature. Equation (3) is an average, best-fit empirical expression based on bearing strength data obtained with a variety of porous solids, such as ceramics, rockfroth, cellular concrete, foam glass, rigid cellular plastics, etc.

It is pertinent to the analysis of the Surveyor data to note that the bearing strength of underdense, (i.e. $p \gg 50\%$) materials, fluff or rockfroth, unlike that of densely packed soils ($p \ll 50\%$) is independent of the gravity field. This is largely due to differences in the nature of forces that come into play during failure. These effects, suggested by equations (1) to (3) have been verified by soil bearing tests performed aboard a Grumman aircraft flying near-Keplerian trajectories (Ref. 3). Test results obtained with densely packed beach sand and loosely sifted pumice are shown in Figure 3. In view of its gravity-dependence, the bearing strength vs porosity relationship of densely packed soils is represented by two curves in Figure 2, one under 1g and the other under 1/6g. These curves are based on an 20-cm. diameter plate about the size of the Surveyor pads. The fluff curve is based on a z/D of about 1/2 and an f(e)/d of 5000 dynes/cm. 2. Dry powders in air, like household dust or talcum powder, have a cohesion of this order due to van der Waals forces of attraction.

As far as dynamic effects on bearing strength are concerned, it is reasonable to assume that in the case of underdense materials they are negligible; however, they could be appreciable if the soil is densely packed, particularly in the low gravity field of the moon (Ref. 3).

In Figure 2, soils that obey the principles of conventional soil mechanics occupy a relatively narrow band in the overall spectrum of bearing strength or porosity represented by porous media. What we term soils, fluff and rock froth are in effect the lower and upper strength envelopes of a vast range of partially consolidated materials. Such materials may encompass the full gamut of porosities and a bearing strength of about six orders of magnitude. When seen in this perspective, the porosity of the Surveyor site (at a bearing strength of about 0.5 kg/cm^2) could be anywhere between 35% to 99%, according to Figure 1, depending upon its cohesion or degree of consolidation. Therefore, a close look at all pertinent aspects of the Surveyor 1 data is necessary to narrow the wide range of porosities or degree of consolidation suggested by Figure 2.

SURVEYOR 1 DATA AND REPORTED ESTIMATES

At this time of writing, Ref. 1 is the only source of published data on Surveyor 1. Briefly, the following preliminary results are reported in this reference on the mechanical and thermal properties of the lunar surface where Surveyor 1 landed.

1. Actual Measurements and Observations

   a.) Bearing Strength: A maximum dynamic foot pad pressure of 0.3 - 0.7 kg/cm^2 is recorded at impact.

   b.) Soil Behavior during Failure: Material appears to be compressed in volume but some lateral displacement of material did occur. The formation of a raised rim around the foot pad depression is also mentioned.

   c.) Dust: No loose dust appears to cover the area. This conclusion is based on absence of erosion under jet impingement and levels of spacecraft surface temperatures consistent with those of clean dust-free radiative surfaces.

2. Estimated Properties

   a.) Static Bearing Strength: 0.35 kg/cm^2. An alternate, two-layer model is also suggested, consisting of a hard material (static bearing strength greater than 0.7 kg/cm^2) overlain by a weaker material to a depth of about 3 cm.

   b.) Soil Parameters: A reasonable choice, considering all available data, is a soil with a cohesion in the range of 1,000 to 4,000 $dynes/cm^2$, and a friction angle between 30 and 40° at a density of terrestrial soil of 1.5 g/cm^3. (We note, no estimate of porosity as such is given; however, the bulk density of 1.5 g/cm^3 corresponds to a porosity of about 45%)

   c.) Thermal Properties: No on-site measurements of lunar surface temperatures are reported. However, based on isothermal eclipse contour maps of Shorthill and Saari[4] an estimated $(k\rho c)^{-1/2}$ or γ of about 800 cgs

units is given for this area. The estimate also appears to be typical of the major portion of the visible lunar surface.

In the following sections we examine whether these measurements, observations and estimates are mutually consistent in the light of recent investigations on the thermal, mechanical and photometric properties of porous media in general and of the lunar surface in particular.

CORRELATION OF BEARING STRENGTH AND THERMAL PROPERTIES

Figure 4 is a graphic summary of analyses reported in Ref. 2 on the correlation of the midnight temperatures T_m, or thermal inertia constant γ , of the lunar surface and bearing strength. The ordinates, T_m or γ , are functions of the thermal conductivity of the cooling materials which encompass the full range of porous media likely to be found on the moon. (The γ ordinate is valid only in region where the thermal conductivity of the material is nearly independent of temperature.) The correlation is based on the fact that both thermal conductivity and bearing strength are primarily functions of the same properties, namely porosity, degree of consolidation and, for particulate media, of grain size (because of the dominance of the radiative component of heat transfer). The analyses exclude effects of surface roughness and internal heat sources. According to Figure 4, exposed bedrock on the moon would exhibit a midnight temperature of about 210°K. No such temperatures have been observed on the moon. Most available data on lunar night temperatures (excluding anomalies) are between 100°K and 130°K. The lowest and highest lunar night temperatures, recently reported by Low[5], are 70°K and 150°K. These temperatures correlate with fluff and porous rock respectively, encompassing about 5 orders of magnitude of bearing strength.

In Figure 4, a cross-hatched vertical column is shown at 0.35 to 0.7 kg/cm^2, the measured or estimated bearing strength of the Surveyor site. For this discussion we will assume that this is also the static bearing strength. Since no direct measurement of the night temperature of this area exists or has been reported, we resort to the estimated γ value of 800 (based on eclipse isotherms of Shorthill and Saari) in order to determine the ordinate of this data point. A γ of 800 intersects the cross-hatched column at a point slightly below the correlation curve. In actuality, the fit of this data is likely to be even better than shown in Figure 4, because a γ of 800 is based on eclipse temperatures whereas the correlation

curve is based on lunation temperatures. It is well known that γ values are generally lower for lunation cooling than for eclipse cooling, probably because denser or more conductive layers below the surface contribute to the surface temperature during a longer cooling transient. It may be concluded, therefore, that the reported bearing strength and γ values for the Surveyor site are reasonable and consistent, particularly if we take into account the possibility that the lunation γ could be as low as 400. This depends on the rate at which the bulk density and/or the cohesion of the material increase with depth. According to Figure 4, γ values of 800 and 400 correspond to lunar midnight temperatures of $105^{\circ}K$ and $123^{\circ}K$ respectively. Earth-based and/or on-site measurements of this temperature would be of great value. If it turns out that this temperature is closer to $123^{\circ}K$ than to $105^{\circ}K$, we may infer that the material at the Surveyor landing site is appreciably more cohesive than the olivine or tektite powder to which it has been compared (Ref. 1). Since experimental data on thermal conductivity (in vacuo) and bearing strength of porous media are very scarce, it is not possible to determine from Figure 4 the separate values of bulk density, cohesion and friction angle of the soil at the Surveyor site. The data point falls into the "ambiguous" region where fluffs, soils and porous rocks meet. Therefore it is necessary to resort to other lines of evidence to determine whether the soil parameters suggested in Ref. 1 are consistent within themselves and with the reported values of bearing strength and γ .

CORRELATION OF BEARING STRENGTH AND SOIL PARAMETERS

The possibility of appreciable soil cohesion suggested by the above analysis of the Surveyor 1 thermal data is not in accord with the soil parameters proposed in Ref. 1. These parameters characterize a soil that is highly frictional and essentially cohesionless, similar to soils described by the dotted curves in Figure 2, for both 1 g and 1/6g. As we established earlier, the bearing strength of such soils is a direct function of the gravity field. According to Figure 2 the bearing strength of the Surveyor site, represented by an horizontal cross-hatched strip, is compatible with a $\rho = 1.5$ g/cm^3 (or a porosity of about 45%) only if we disregard gravity effects. (Notice that the 1g-soil curve crosses the region where the horizontal strip intersects a vertical line at 45% porosity).

There are two soil models which seem compatible with a 0.35 to 0.7 kg/cm^2 bearing strength experienced in a 1/6 g gravity field. The first model is defined in Figure 2 by the intersection of the horizontal strip with the 1/6g-soil curve. This point is located at a porosity of about 35% which corresponds to a ρ of 1.8g/cm^3. Such a soil would have a bearing strength of at least 2 kg/cm^2 under 1g. The second model is located somewhere in the shaded, "partially consolidated" region, ($p >> 50\%$) where bearing strength is independent of the gravity field. Both models have the same bearing strength but differ significantly in their bulk density, cohesion, and friction angle. The former is densely packed ($\rho > 1.5$ g/cm^3) and essentially cohesionless; its bearing strength is due mostly to gravity-dependent interparticle frictional forces. The latter is loosely packed ($\rho < 1.5$ g/cm^3) and held with gravity-independent cohesive forces; little or no internal friction is likely to be developed during the failure of this model.

The underdense-cohesive model appears to be a better option in view of current consensus on the high porosity of the lunar surface and the thermal properties of the Surveyor landing site as analyzed above.

There are three additional lines of evidence which support the underdense and/or cohesive nature of the Surveyor landing site. In the order discussed below, these are: absence of loose dust; mode of soil failure; the microstructure of the undisturbed surface as revealed at a grazing angle of illumination.

Absence of Loose Dust

The dotted "soil" and "fluff" curves in Figure 2 are based on a cohesion on the order of van der Waals forces of attraction. The cohesion of 1000 to 4000 dynes/cm^2 assumed in the Surveyor Report is of this order. However, the apparent stability of the lunar surface during the jet impingement test and the dust-free condition of spacecraft radiative surfaces suggest a degree of cohesion between the lunar granules greater than those due to van der Waals forces. (It would be very instructive to simulate the Surveyor jet test in the laboratory). According to Figure 1, at a bearing strength of about 0.5 kg/cm^2 cohesion is possible only at porosities above 50%.

By increasing both porosity and cohesion we do not necessarily alter the thermal parameter γ or $(k\rho c)^{-1/2}$, because a decrease in ρ (due to an increase in porosity) would be compensated by a corresponding increase in k, since we have made the material more conductive by postulating higher cohesion. Thus, all four aspects of the Surveyor data, namely, γ, bearing strength, gravity field and the jet test, are satisfied by a more porous and cohesive material than currently assumed. In Figure 2, such materials occupy the partially consolidated region represented by the shaded area. In this region, the porosity of an aggregate at about 0.5 kg/cm^2 bearing strength could be anywhere between 54% to 99% depending upon its degree of consolidation. It is not possible to narrow these limits further on the basis of this evidence.

Mode of Soil Failure

A second argument in favor of high porosity may be based on the type of soil failure under and around the pad as evidenced by published photographs. In Ref. 2 we established that

densely packed soils (porosities below 50%) fail predominantly in lateral shear. Underdense soils (porosities above 50%) fail predominantly in local shear. The former mode is characterized by massive movement of soil away from the pad. The latter is characterized by volumetric compression of the soil in the direction of the applied load (see Figure 1).

Apparently both modes of failure have taken place under the Surveyor pad. This fact is recognized in Ref. 1, but no attempt is made to assess the predominance, if any, of one mode of failure over the other. Photographs of footpads 2 and 3 are shown in Figure 5. (Pad 1 could not be photographed.) These photographs support the view that the soil under and around the pads has failed predominantly by local shear.

The impact of the Surveyor on the lunar surface and the lateral deflection and spring back of the leg (as evidenced by the gap between soil and pad) could produce a lateral displacement of the soil as mentioned in Ref. 1. Whether this displacement is due to lateral or local shear could not be determined from the profile of the disturbed soil. In Figures 5a and 5b, there is some evidence of "throw out" but no conspicuous raised rim to indicate lateral shear. The material thrown out does not appear sufficient to account for all the displaced material, thus suggesting that the rest of the material has been compacted laterally and vertically, like crunchy snow. According to Figures 1 and 2, this type of failure indicates a porosity above 50%. If there were no material thrown out of the hole, it would be reasonable to suggest a porosity of at least 60 to 70% for the undisturbed soil. However, since there is some evidence of throw-out, we will tentatively suggest 60 to 70% porosity as an upper rather than a lower limit. These porosities correspond to a bulk density of about 1 g/cm^3.

If photographs of the disturbed zone were taken at various sun angles during the day, it would be possible to determine the volume of the material above the originally undisturbed surface and assess the relative contributions of lateral and local shear. Such a study

would be very desirable to confirm or refine our estimates of porosity. Knowing bearing strength and porosity, it should then be possible to make a better estimate, preferably by means of experiments, of cohesion and friction angle.

The best evidence for the underdense-cohesive nature of the Surveyor landing site is given by the imprint of the crushable honeycomb block shown in Figure 6. The collapsed floor of the depression, the sharp edges around it, and complete absence of throwout or "bulge" outside the disturbed zone are excellent clues to the underdense (i.e. $p \gg 50\%$) nature of the material. The vertical edges around the depression also suggest that the lunar granules adhere to one another instead of tumbling down like grains of sand. This adhesion could be the result of "vacuum cold welding", a phenomenon recently investigated in various laboratories. Experimental evidence to this effect is shown in Figure 7. To achieve the observed adhesion, it was necessary to outgas the soil particles by continuously tumbling them in a 10^{-10} torr vacuum (Ref. 6).

3. Microstructure of the Undisturbed Surface

The early Surveyor photographs taken at relatively high sun angles did not give so true an indication of the complexity of the lunar surface at a millimeter scale as subsequent photographs taken at grazing incidence. One such photograph is shown in Figure 8a. A close-up view of a specimen of porous furnace slag photometrically analogous to the moon is shown in Figure 8b. The scale of roughness in both photographs is about the same.

A visual comparison of Figures 8a and 8b reveals an interesting similarity in microstructure or "surface porosity", particularly if proper allowance is made for obvious differences in the resolution of details and the sharpness of shadows. The slag specimen has a bulk porosity of about 70%. The inference of a similar porosity for the Surveyor site is based not merely on a visual comparison of the

two photographs but also on the following reasoning based on the results of extensive photometric investigations [6] a) There is a correlation between photometry and surface roughness or porosity. b) Porosities that are most compatible with the average photometric properties of the moon at all longitudes are between 70 and 80%. c) The Surveyor photographs exhibit reflection properties that are typical for the lunar surface. These propositions will be briefly substantiated.

a. In Figure 9, the porous slag specimen is shown with two other specimens, a piece of smooth solid rock with essentially 0% porosity and a piece of sea coral with a porosity much greater than 70%. The photometric signatures of all three specimens and of the "average moon" at 0°, 30° and 60° viewing angles are also shown in Figure 9. The slag at 70% porosity shows the best fit with the lunar band. Also, the results show a clear correlation between roughness or surface porosity and the photometric function. The area under the photometric curve can be used as an index of porosity.

b. Additional photometric experiments were performed at Grumman in which the furnace slag was broken, ground, sorted in particles ranging in size from microns to centimeters and packed at porosities ranging from 50% to 70%. The results, reported in detail in Ref. 7, show clearly that the photometric match with the moon is best at 70% porosity but deteriorates progressively at lower porosities.

c. Photometric curves of the Surveyor site could be constructed from photographs taken during the insolation. Such data have not yet been reported. However, the published photographs exhibit clear evidence of backscatter at 0° degree phase and rapid drop in brightness at increasing phase angles as shown in Figure 10a. The rapid increase of brightness toward the top of the shadow of the spacecraft (where the camera is located) and the obliteration of details in

this region are characteristics of rough and porous surfaces that backscatter light like the moon. At this angle of illumination, the Surveyor landing site, Figure 10a, shows a striking photometric similarity to an aerial photograph of the Surveyor Lava Flow, Oregon, taken under the same condition of illumination, Figure 10b. (The name of this lava flow is central Oregon, near the city of Bend, is purely coincidental.) Notice a similar increase in brightness and obliteration of details in the "opposition region" (near zero phase angle) around the shadow of the aircraft. Photometric measurements of specimens from this site show an excellent match with the lunar curves[8].

The microstructure of the Surveyor landing site appears also to be compatible with the average polarimetric properties of the moon. Our latest theoretical and physical models at Grumman indicate that it is not necessary to postulate fine dust to account for these data. These investigations will be reported in a subsequent publication.

Pending the availability of quantitative data, it seems reasonable that the photometric properties of the Surveyor landing site, like its polarimetric and thermal properties, do not significantly differ from average values for the moon which, according to our experiments, correlate with porosities of the order of 70%.

Another optically relevant but puzzling aspect of the Surveyor data is the difference in albedo between the surface and the material underneath. Experiments in recent years on the darkening of silicate powders exposed to a simulated solar wind have led us to expect that the lunar surface would be darker than the subsurface material. However, quite the opposite appears to be the case judging from the reflectivity of the ejecta and the undisturbed surface around the Surveyor pads, Figure 5. This writer has no explanation to offer for this observation other than to raise the question whether the solar wind (assuming it

reaches the surface of the moon) or some other agent has a "bleaching" rather than a darkening effect on the lunar surface. The fact that the highlands are brighter and older than the maria, gives some validity to this surmise. More recent experiments performed by D. Nash of the Jet Propulsion Laboratory (private communication) show no darkening of powders when they are exposed to a simulated solar wind under conditions believed to approximate more closely those of the lunar surface.

CORRELATION OF ELECTRICAL AND MECHANICAL PROPERTIES

The dielectric constant of materials is also a sensitive function of porosity. This dependence is shown in Figure 11 based on data reported by Brunschwig et al[9].

The dielectric constant of the lunar surface can be determined by radar reflectivity measurements or by radiometric observation of the thermal emission. Radar and radio techniques have generally yielded values of 2.8 and 1.8 respectively. This contradiction has stimulated a great deal of debate in recent years but it appears to have been resolved now by Hagfors[10]. By sending out circularly polarized waves and discriminating between components of the echo reflected from the surface and from harder layers beneath the surface, Hagfors was able to resolve the two types of previous measurements in terms of a surface layer of thickness greater than the radar wavelength (about a foot in these measurements) whose dielectric constant is about 1.8 and which overlies a material whose dielectric constant is between 4 and 5.

According to Figure 11, a dielectric constant of 1.8 corresponds to a porosity of 70% for quartz. This value is surprisingly close to our estimate based on the pattern of the disturbed soil and the microstructure of the undisturbed surface. It appears that the mechanical, thermal and optical properties of the Surveyor landing site are in substantial agreement with the average electrical properties of the lunar surface obtained by radar and radiometric measurements. It is possible and very desirable to estimate the dielectric constant of the Surveyor site from the landing radar reflectivity data. Presently, all preliminary lines of evidence appear to converge toward an underdense material which, by virtue of its high porosity, must be necessarily cohesive or partially consolidated to account for the bearing strength measured by Surveyor.

CONCLUSIONS

Surveyor 1 has landed on an area of the moon that appears to be covered, to an unknown depth, with an underdense, partially consolidated material. Mechanical, radiothermal, radar and photometric lines of evidence indicate that the in-situ porosity and cohesion of this material have been underestimated and its friction angle overestimated. A bulk density of 1 g/cm^3 (corresponding to 60-70 % porosity) seems to account for the observations and measurements better than the previously proposed bulk density of 1.5 g/cm^3. This revision entails an upgrading of cohesion by about 2 orders of magnitude (from 10^3 to 10^5 dynes/cm^2). The cohesion appears to be due to solid bridges between the grains rather than to molecular forces of attraction. The frictional and dynamic components of bearing strength are probably negligible.

Such soils do not commonly occur on the earth, but they appear to be the rule rather than the exception on the moon. Rock froth or semi-welded tuffs (a form of "volcanic snow") are their closest terrestrial counterparts. Much remains to be learned about the mechanical, optical, thermal and electrical properties of these materials: the principles of conventional soil mechanics do not account for the behavior of highly porous media during failure; although much progress has been made in understanding the photometry of complex geometries, the polarimetric properties of such surfaces remain largely a puzzle; finally, the quantity and quality of test data on the thermal conductivity and dielectric constant of postulated lunar materials leave much to be desired.

Despite these limitations, we see no obvious contradictions between the Surveyor findings, astronomical lunar data and laboratory experiments, when these are interpreted in terms of an underdense-cohesive model which, incidentally, was postulated in a pre-Surveyor study at Grumman.

Finally, the usefulness of earth-based lunar investigations need not be limited to improving our ability to interpret lunar probe data as illustrated in this study. An important lesson that can be learned from the mission of Surveyor 1 is the extent to which the physical properties of its landing site correlate with earth-based astronomical measurements and laboratory experiments. This lesson is more than of an academic interest. It opens up the possibility of utilizing future lunar landing sites as "calibrated bench marks" for the remote investigation of unexplored or inaccessible areas of the moon. The physical properties of these areas could be inferred with greater confidence from remote sensor data if similar data are obtained on specific lunar sites whose physical properties are known. The concurrence between Surveyor and pre-Surveyor lunar data we have noted above lends much validity to the "coordinated" analysis of the reflection and thermal emission of remote bodies.

In years to come, when the problems of lunar landing and logistics are solved, we will be looking for "interesting" lunar sites to explore. No better approach suggests itself at this time than sifting remote sensor data in order to sort out areas that appear anomalous at one or more wavelength. The moon lends itself very well to this kind of investigation because of its lack of an atmosphere and vegetation. There is now sufficient knowledge to support the view that "average" lunar photometric and radiometric data can be correlated with physical properties of the lunar surface such as roughness, porosity, hardness, internal heat sources, etc.[2, 7, 11]

However, much remains to be learned about the engineering and scientific implications of lunar "anomalies". Recent observations of the eclipse and night infrared thermal emission of the moon suggest that the lunar surface is not so homogeneous on a kilometer scale as it appears to be at much larger scale. It is reasonable to expect that more anomalies, including those at shorter and longer wavelengths will be discovered by subsequent high-resolution observations from the earth and from lunar orbit.

Theoretical and experimental studies to interpret such data should parallel or preferably precede on-site lunar measurements and remote observations.

These studies could be very useful in determining what kind of new lunar data are urgently needed and how the new observation should be made in terms of wavelength, resolution, lunar phase and location on the moon. This study has revealed for instance that, next to bearing strength, the most important measurements Surveyor can make are the bulk density or porosity of the material and the photometric and nighttime temperatures of the surface. Polarimetric measurement can also be performed at little extra cost. Lack of knowledge of porosity vs. depth of the outermost layer of the moon has been the major stumbling block in interpreting almost every aspect of the lunar astronomical data.

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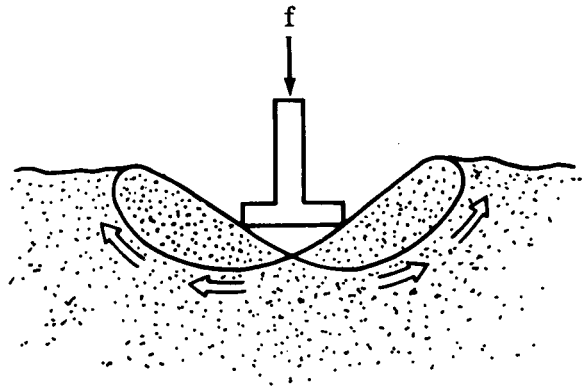
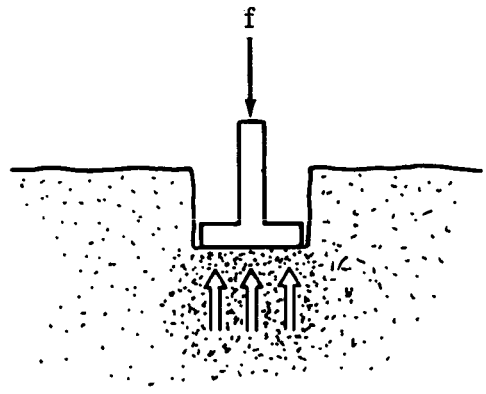


(a) Shear Failure,
Porosity < 50%



(b) Compressive Failure,
Porosity > 50%

Figure 1
Modes of Failure in Porous Media

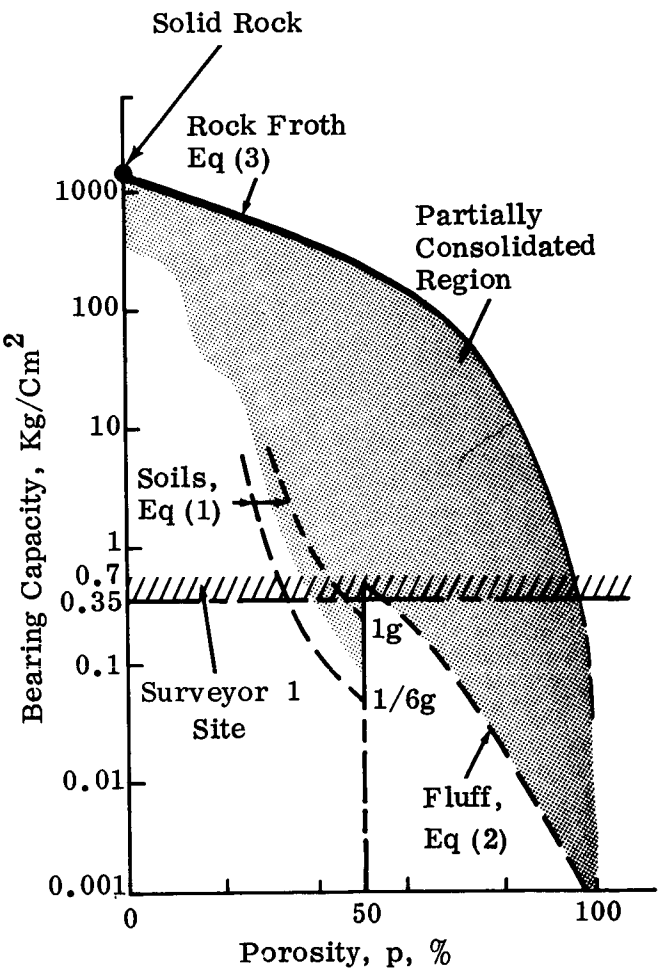
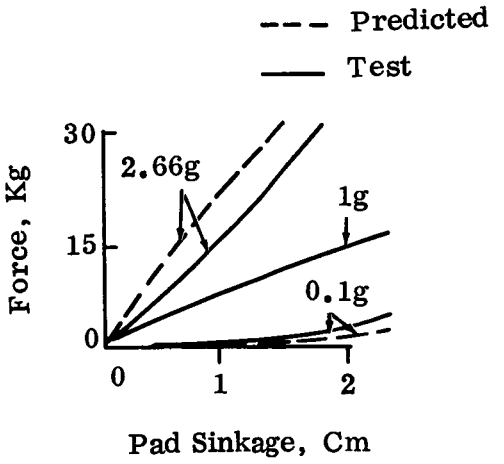
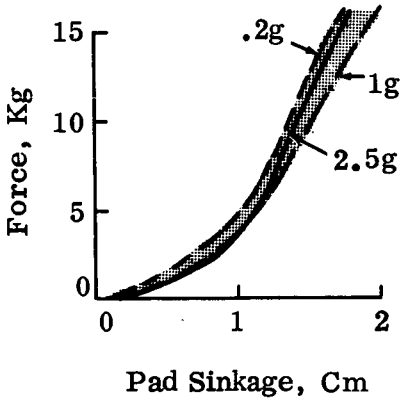


Figure 2
Bearing Capacity of Porous Media, Ref (2)



a. Densely Packed
Beach Sand, p < 50%



b. Loosely Sifted
Pumice, p > 50%

Figure 3
Soil Bearing Strength of Particulate Media
Under Varying g's, Ref (3)

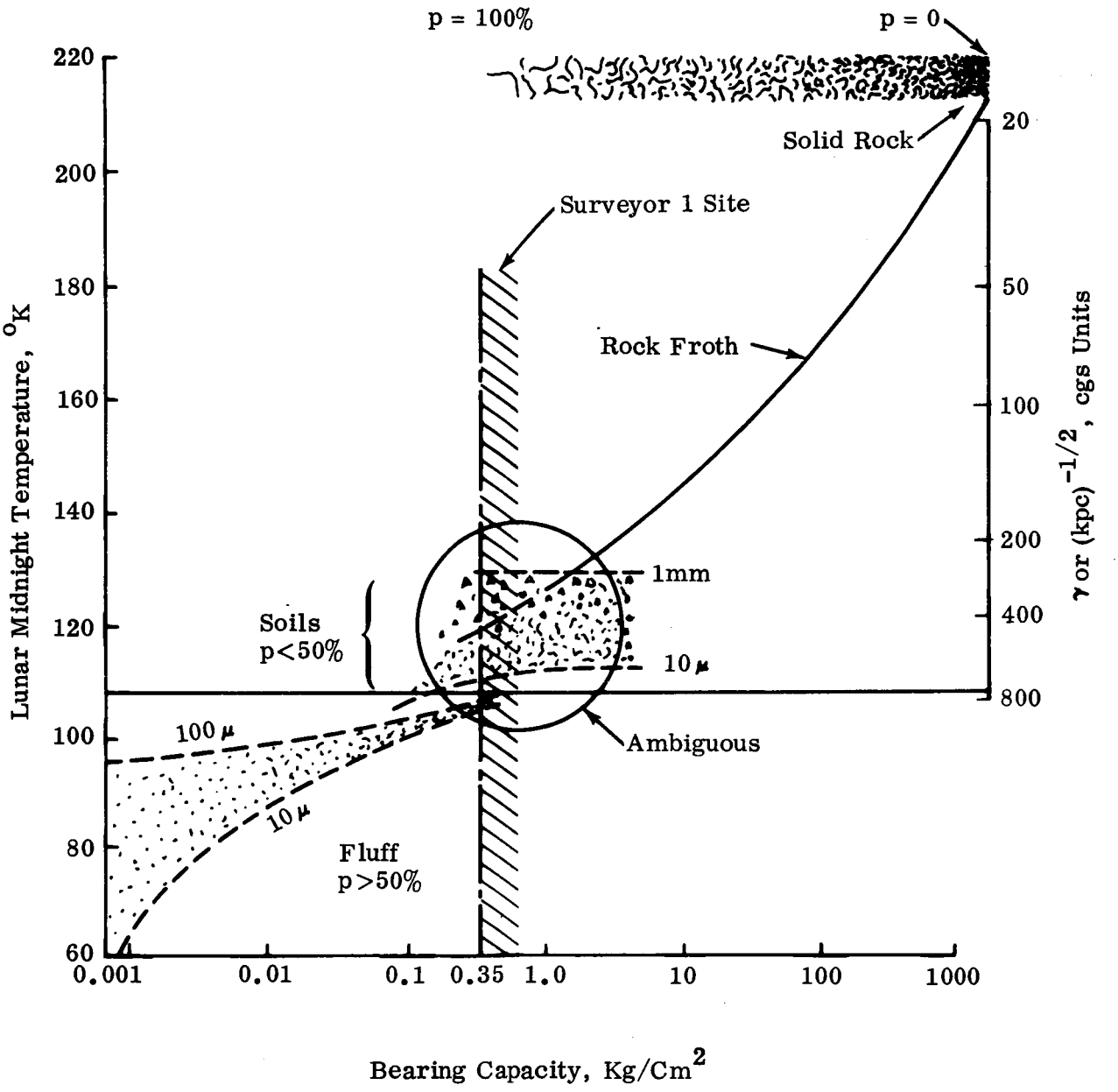
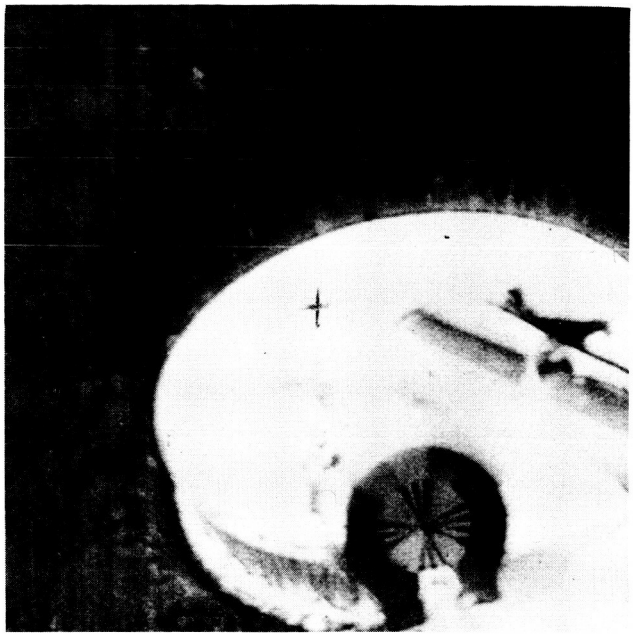
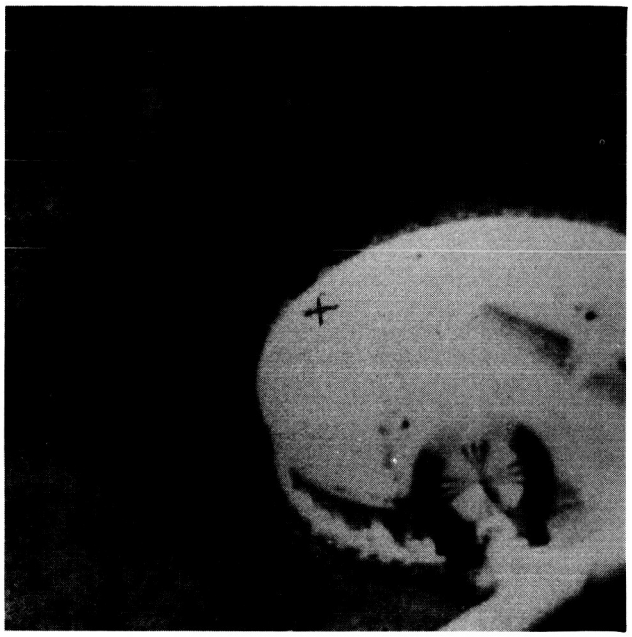


Figure 4
Correlation of Thermal and Mechanical Properties of the Lunar Surface, Ref (2)

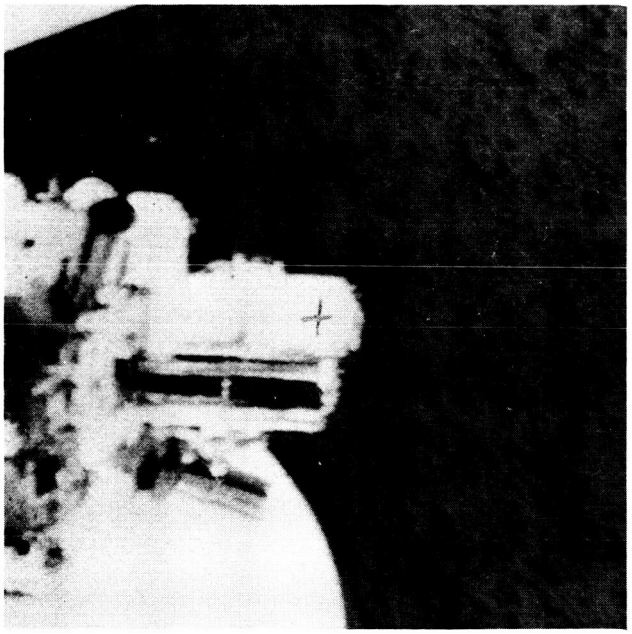


a. Pad 2 (Low Sun)



b. Pad 2 (High Sun)

c. Pad 2 (Close-Up)



d. Pad 3

Figure 5
Imprints of Surveyor 1, Ref (1)

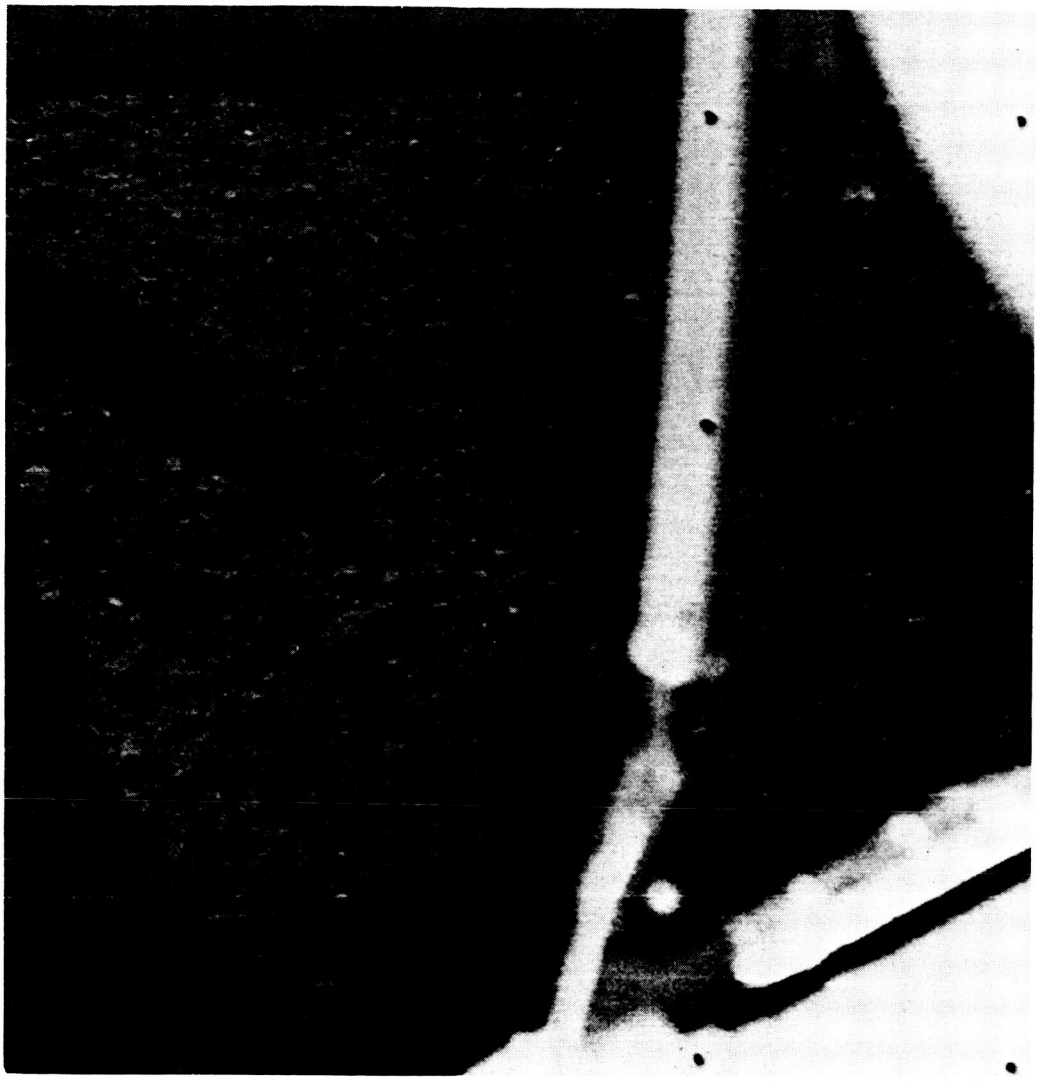
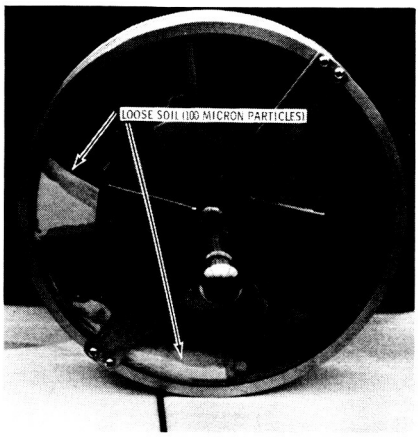
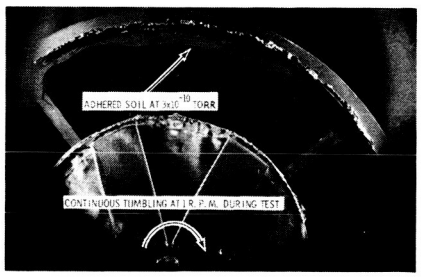


Figure 6
Imprint of Crushable Honeycomb Block Under Surveyor 1, Ref (1)

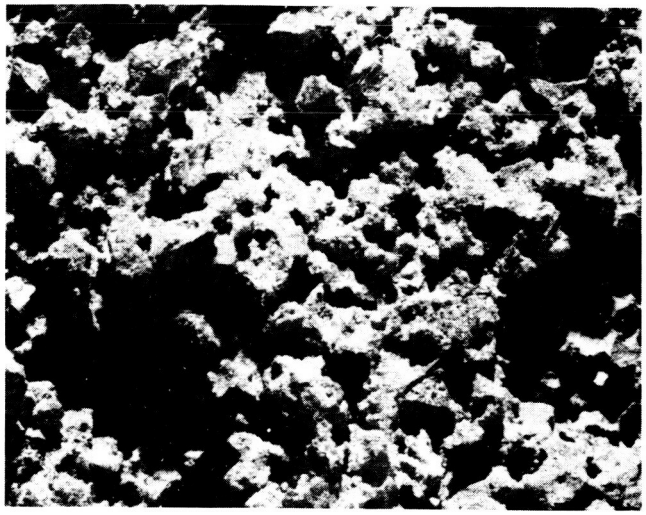


(a) Before Vacuum Exposure

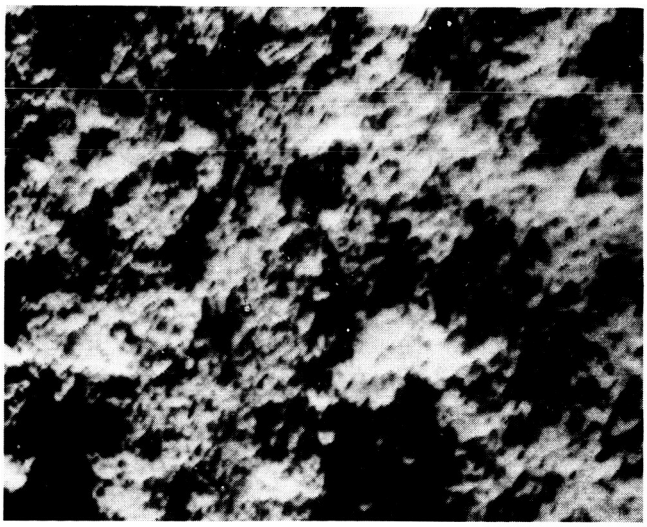


(b) After Vacuum Exposure (10^{-10} Torr)

Figure 7
Soil Adhesion in Ultra High Vacuum, Ref. (6)

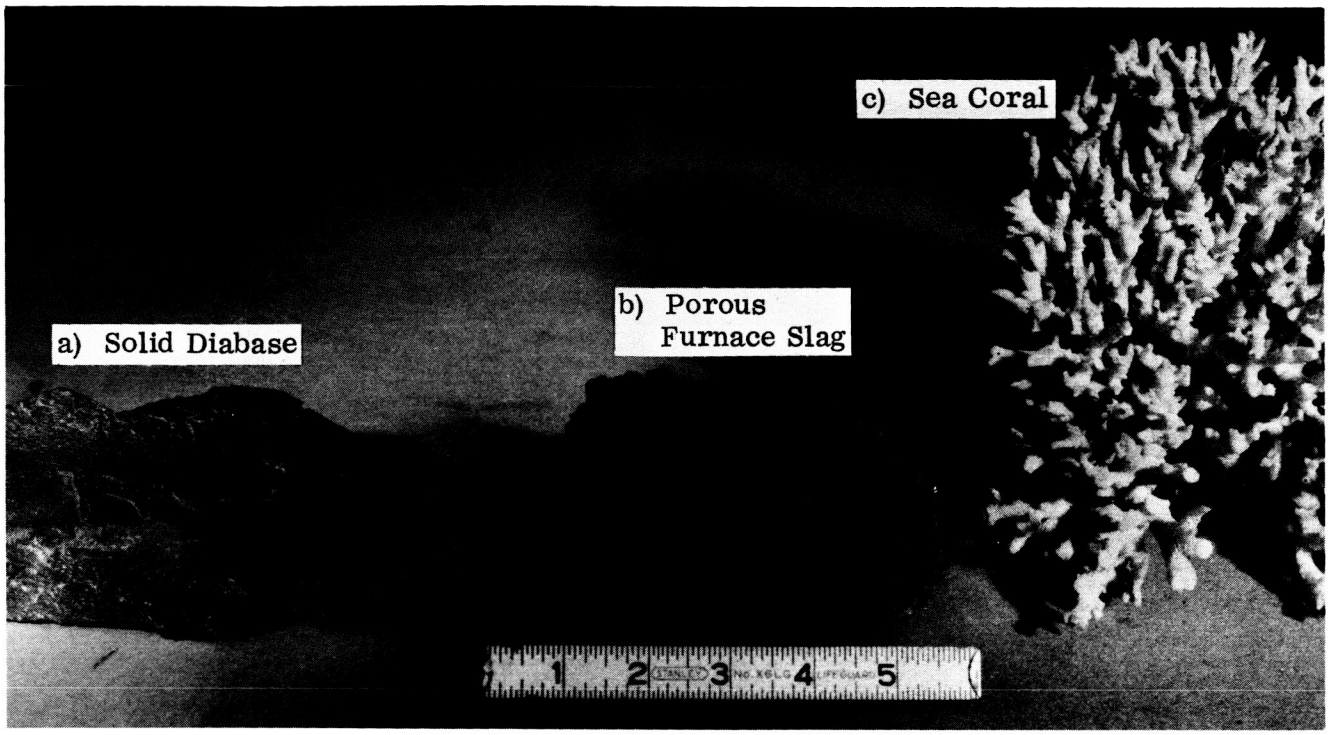


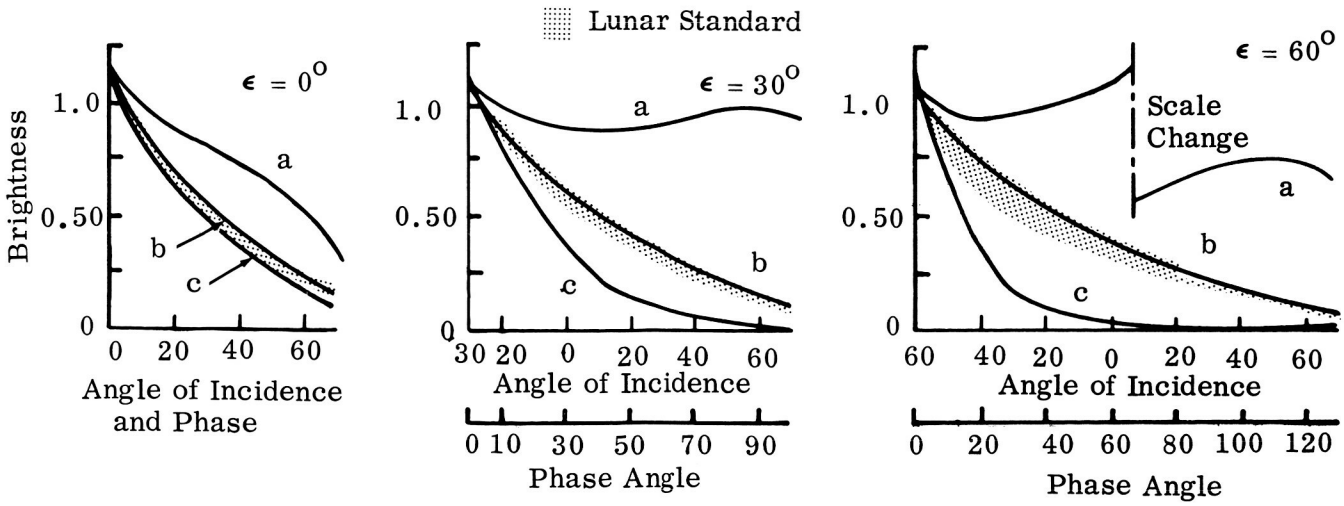
(a) Surveyor 1 Site at Grazing Incidence



(b) Porous Furnace Slag

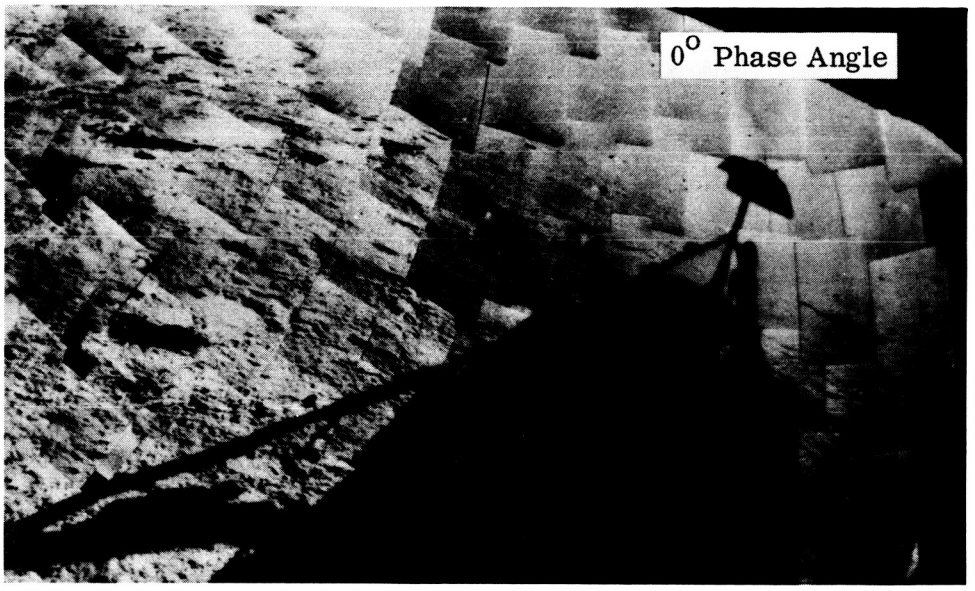
Figure 8
Microstructure of Lunar Surface and
Lunar Photometric Analog,Ref (1 and 7)





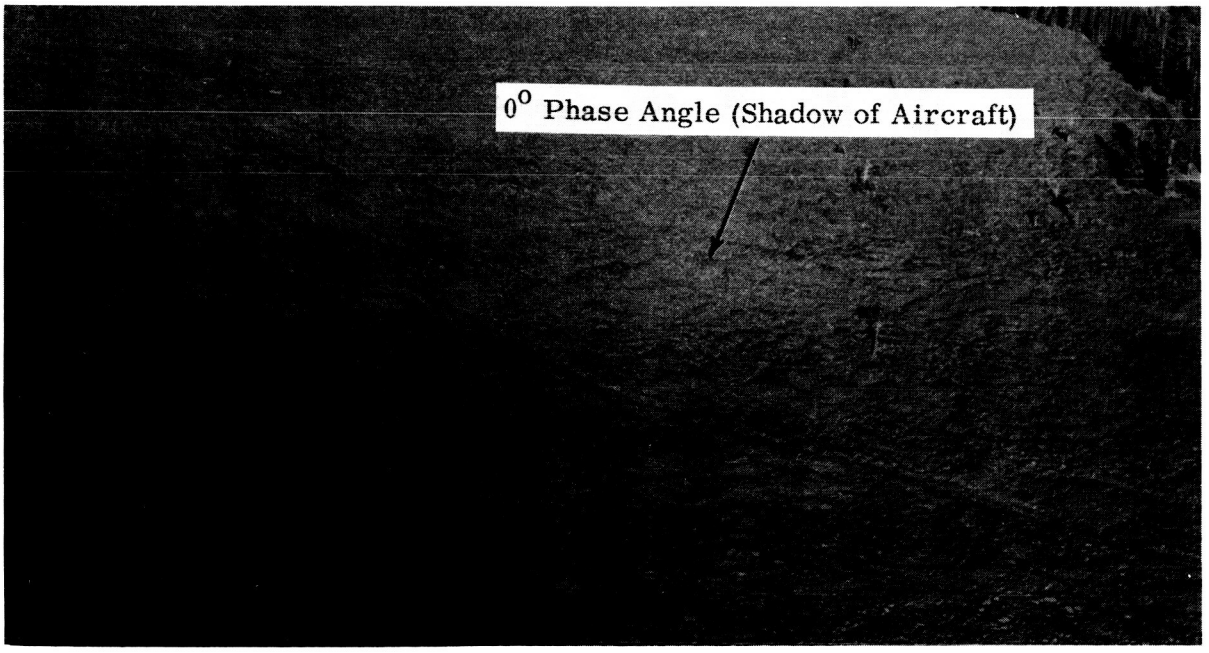
d. Angle of Incidence and Phase Angle vs Brightness

Figure 9
Correlation of Photometric Function and Surface Porosity, Ref (7)



Increasing Phase Angle
and Decreasing Brightness

(a) Surveyor Landing Site



Increasing Phase Angle
and Decreasing Brightness

(b) Surveyor Lava Flow, Oregon

Figure 10
Brightness of Surveyor 1 Landing Site and Oregon Lava Flow at 0° and Larger Phase Angles, Refs (1, 8)

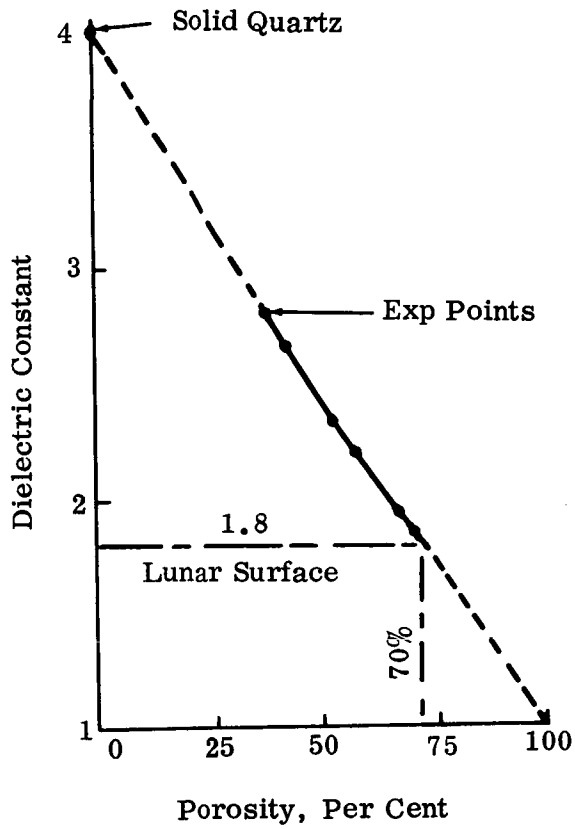


Figure 11
Variation of Dielectric Constant With
Porosity, for Sand, Ref (9)