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ESTIMATES OF SOME PHYSICAL/MECHANICAL PROPERTIES OF MARTIAN ROCKS AND SOILLIKE MATERIALS

by

H. J. MOORE[1]

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[1] U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025

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H. J. Moore
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

ABSTRACT

This paper addresses questions on Martian surface materials (exclusive of the polar regions) that were posed at a Sand and Dust Workshop in February, 1991. Materials thought to be most likely encountered on Mars are dust, soillike materials, sand sheets and dunes, and bedrock and rock fragments. In response to a need expressed by engineers attending the workshop, selected physical/mechanical properties of these materials are discussed: grain size, hardness, and shape; density; friction angle; cohesion; compressibility; adhesion; thermal inertia; and dielectric constant and loss tangent. Numerical values of these properties are presented for each material in tables. Some properties, such as bearing strength, are only briefly discussed because they are derived from other properties. Additionally, other factors affecting the surface materials and their responses to loads, such as surface gravity, are discussed.

In conclusion, four specific questions posed at the workshop are addressed. The principle conclusion is that most Martian surface materials appear to be similar to those on Earth, because of the magnitudes of the average thermal inertia and radar reflectivity and the correlation of thermal inertia and radar reflectivity. On this basis, it is concluded that exploration on the surface of Mars is an achievable goal.

INTRODUCTION

This paper addresses questions on the physical/mechanical properties of Martian surface materials that were raised at the Sand and Dust Workshop sponsored by the NASA Mars Science Working Group and held 4 and 5 February, 1991 at Arizona State University, Tempe, Arizona. Answers to these questions -- based on observations and measurements supplemented by best estimates -- are needed by engineers making preliminary design studies for future spacecraft to Mars and for vehicles and human habitats on Mars.

Five materials considered representative of most of the surface (excluding polar regions) and the disturbed states of two materials are described and their properties quantified where possible. The properties quantified include: grain size, hardness, and shape; density; friction angle; cohesion; compressibility; adhesion; thermal inertia; and dielectric constant and loss tangent. These properties are listed in tables. Information that engineers have requested on some properties are derived from other properties and include: angle of repose, bearing strength, penetration resistance, and rutting and washboarding. Although briefly discussed, these derived properties are not described in detail here because of the many possibilities; these properties should be derived by engineers trained in Soil Mechanics and Off-road Locomotion. Other factors related to the surface materials and their responses to loads are also discussed: surface gravity, water and water-ice, pore fluids, heterogeneity, geologic processes, and eolian processes.

PHYSICAL/MECHANICAL PROPERTIES

The properties discussed below are selected from a larger list provided by engineers at the Johnson Spacecraft Center, Houston, Texas. They were chosen because most of them are used to obtain the derived properties described later; others are separately important for design purposes.

Grain Size, Hardness, and Shape

Soillike materials are composed of rock, mineral, and/or mineraloid grains that are held together by interparticle forces of various magnitudes. The grain size of a soillike material may range from fractions of a micrometer to decimeter sizes. The grains may be well sorted, as in some sands, or poorly sorted, as in ejecta from impact craters. Aggregates of small grains form clods of different strengths and sizes. Similarly, rocks are made of aggregates of grains. Most grains that make up rock fragments are smaller than the fragments.

The grain size of the soillike materials sampled at the Viking landing sites appears to be very fine, because the specific surface of the material estimated from desorbed gases is near 17 m^2/g (Oyama and Berdahl, 1977; Ballou et al., 1978). Simple geometric calculations using this area imply a grain size near 0.14 micrometers, but the physical sizes of grains are 10 to 100 times larger (Fanale et al., 1971). Thus, the physical grain size is in the range of 0.1 to 10 micrometers (Moore and Jakosky, 1989). On Mars, aggregates of these grains form clods up to about 0.04 m or so across of various strengths. Some of these clods may include millimeter-size rock fragments and mineral grains as well as centimeter-size rock fragments (Moore et al., 1987; Dale-Bannister et al., 1988; Arvidson et al., 1989). The range of grain sizes of Martian dune sand can be estimated as that corresponding to the minimum threshold friction speeds required for saltation (e.g., Iversen et al., 1976). This range is near 100-125 micrometers. Some sands may be coarser than this (Christensen, 1983), and lag materials with particle sizes up to several centimeters are possible. Rock fragments and blocks from a few centimeters to several meters across were directly observed at the Viking landing sites (Binder et al., 1977; Moore et al., 1979, 1987).

Grain hardness may be expressed by the Mohs hardness scale (Dana and Ford, 1954, p. 214). In this scale, soft minerals with a hardness of 1 (talc) can be scratched with a finger nail, but harder minerals with a hardness of 7 (quartz) will scratch glass, but they cannot be scratched with a knife blade. The hardnesses of two common minerals in basaltic rocks, pyroxene and olivine (5-7), are used for sands and rocks, and typical hardnesses for clay minerals (1-3) are used for grains in dusts and soillike materials (e.g., Winchell and Winchell, 1956, pp. 362, 398, 402, 498). One soillike Martian material includes some hard mineral and rock grains as well as soft clay grains (Moore et al., 1987). As a guess, hardnesses of clods should be less than 1 or 2.

Grain shape ranges from rounded to angular. Grains of sand transported by the wind are probably rounded to subrounded. Grains and fragments in the ejecta of impact craters are probably subrounded to angular. Descriptions of rock shapes can be found in Garvin et al. (1981) and Sharp and Malin (1984).

Density

Density is the mass per unit volume (kg/m^3) of a substance. For natural materials, the term bulk density (rho_b) is used, because most of them are composed of aggregates of rock, mineral, or mineraloid grains with variable grain density (rho_s) and pore spaces between the grains; the pores may contain fluids that also have densities. The contribution of the Martian atmosphere to the bulk density is negligible. Grain densities assumed for sands are those of basaltic rocks, while those of the soillike materials are those of a nominal clay mineral (e.g., Winchell and Winchell, 1956, p. 362).

Porosity (n) and void ratio (e) are properties related to bulk density. Porosity is the volume fraction of pores in the material (e.g., Hough, 1957, p. 32) and is given by:

$$n = (rho_s - rho_b) / rho_s$$

Void ratio is the ratio of volume of pores and solids (e.g., Hough, 1957, p. 32) and is given by:

$$e = (rho_s - rho_b) / rho_b$$

Lower-bound values of bulk densities or upper-bound void ratios of Martian dusts present a significant engineering unknown. Evidence for the magnitudes of bulk densities of Martian surface materials comes from the Viking landers and analyses of quasi-specular radar echoes; these echoes sample the uppermost fraction of a wavelength of the Martian surface. The bulk density of disturbed drift material is 1,100 $\pm$ 150 kg/m^3 according to estimates at the Lander 1 site made by the X-ray fluorescence experiment (Clark et al., 1977), but the in situ bulk density of drift material may be lower than this, because the estimated friction angle is small and the friction angle of a soillike material appears to be related to bulk density (Mitchell, et al., 1972). The other soillike materials appear to have larger bulk densities than drift material (Moore et al., 1987). Densities of rocks on Mars are probably like those of rocks on Earth (Moore et al., 1987; Arvidson et al., 1989; Moore and Jakosky, 1989).

Model-dependent bulk densities can be inferred from relative dielectric constants (Campbell and Ulrichs, 1969; Olhoeft and Strangway, 1975; Moore and Jakosky, 1989), and relative dielectric constants can be estimated from the normal reflectivities of quasi-specular radar echoes (e.g., Tyler et al., 1976). For radar transmissions with wavelengths near 12.6-cm, average normal reflectivities of the echoes from Mars are near 0.06-0.07 (Downs et al., 1975; Harmon et al., 1982; Harmon and Ostro, 1985; Thompson and Moore, 1989), but echoes of continuous-wave transmissions from the Tharsis region are much lower than average (0.02-0.05), and those from delay-Doppler analyses are even lower (0.015) (Downs et al., 1975; Jakosky and Christensen, 1986). The inferred average bulk density for Mars is about 1,400 to 1,500 kg/m^3, but bulk densities of the Tharsis region are 950 (or perhaps 800) to 1,300 kg/m^3. Similar results are obtained by using the equation of Olhoeft and Strangway (1975). It has been suggested that bulk densities of Martian surface materials may range from 1,000 to 2,000 kg/m^3 on the basis of radar observations at 70-, 12.5-, and 3.8-cm wavelengths (Simpson et al., 1977).

Friction Angle

Friction angle and cohesion are two parameters that describe the strength of soillike materials and rocks. The conditions for failure are commonly described using the Mohr-Coulomb criteria (e.g., Terzaghi, 1948, Chapt. 2, p. 7-25):

$$T = T_o + (S-p) * \tan (phi),$$

where T is the shear stress parallel to the failure plane, T_o is the cohesion, S is the stress normal to the plane of failure (which may be altered by pore fluid pressures, p), and phi is the friction angle. Tan (phi) is the coefficient of friction. For cohesionless materials such as dry, loose sand, the shear stress required to initiate a sliding motion along the plane is equal to the friction term (S * tan (phi)). Most soillike materials and rocks have cohesion for various reasons so that a shear stress in excess of the cohesion, T_o, is required for failure of the material.

Friction angle is a function of void ratio, grain shape, and grain mineralogy. On Earth, soillike materials commonly have friction angles near 30° to 40°, but smaller friction angles are possible if bulk densities are small. Sands commonly have friction angles near 34° to 42° and rocks near 40° to 60°. Rather crude estimates of friction angles for soillike materials at the Viking landing sites range from 18.0° ± 2.4° (drift material) to 34.5° ± 4.7° (crusty to cloddy material) (Moore et al., 1982, 1987; Arvidson et al., 1989; Moore and Jakosky, 1989).

To estimate friction angles for other areas on Mars, a relation similar to a lunar-regolith simulant could be used (Mitchell et al., 1972):

$$\tan(\text{phi}) = 0.725 * 1 / e,$$

where phi is the friction angle, 0.725 is a constant estimated by the author from the plot of Mitchell et al. (1972), and e is the void ratio. However, the constant, 0.725, does not apply to all soillike materials.

Cohesion

Cohesions of soillike materials appear to be related to porosity, grain size, moisture content, mineralogy, and cementation. Cohesions of dry, clayey silts ranges from 10 to 30 kPa (Gibbs et al., 1961), but smaller and larger cohesions are possible. Cohesions for the soillike materials at the Viking landing sites have been estimated to range from less than 1 to about 11 kPa (Moore et al., 1982, 1987; Arvidson et al., 1989; Moore and Jakosky, 1989), but larger cohesions are possible for Mars. There is evidence that the cohesion of the soillike materials at the landing sites is partly related to cementation by SO_3 and Cl compounds (Clark et al., 1982). Martian sands may be cohesionless because those that saltate and form dunes require very meager to non-existent interparticle forces. The rocks on Mars were never sampled, but analogy with terrestrial rocks suggests that cohesions near 1 to 10 MPa are probable.

Mitchell et al. (1972) found that the logarithm of cohesion of their soillike lunar-regolith simulant is inversely related to porosity:

$$\log_e (C_o) = A - B * n,$$

where C_o is cohesion (in kPa), A and B are constants, and n is porosity (volume fraction of voids). Analyses by the author suggest that a similar relation exists for kaolinite (Ko, 1971), but the values of A and B are different. Kaolinite is a plausible mechanical-properties analog for dust on Mars. Tables 1-9 include the constants A and B for kaolinite and a lunar-regolith simulant (Ko, 1971) and a guess for silt.

Compressibility

Compressibility is the relation between applied load and void ratio (e.g., Hough, 1957, p. 97-121). Compressibility of a soillike material is a function of initial void ratio, cohesion, friction angle, the pore fluid, grain hardness, applied load, and history (previous loading, vibration, cementation, etc.) (e.g., Hough, 1957, p. 104-112). Compressibility is introduced here to show that the void ratio of a soillike material near the surface of Mars is probably not the same as that at depth because of lithostatic loading; rather, void ratios will decrease and bulk densities will increase with depth. The exact relation to use for Martian dusts that settle from the atmosphere and then accumulate over tens of thousands of years is unclear. However, even a rather pessimistic model would suggest that spacecraft will not "sink out of sight," but vehicles that are not suitably designed might have difficulty.

The "virgin" compressibility (e.g., Hough, 1957, p. 104) can be expressed by:

$$\log_e (P) = X - Y * e,$$

where P is the compaction load (in Pa), X and Y are constants that vary with the material and initial void ratio, and e is the void ratio. There is a maximum void ratio (e_o) for each material and a minimum (e_m) near 0.4 for materials with hard grains (silt and sand). Previous loading histories will alter this relation. Some possible general effects of previous loading histories on compressibility and the predictions of two compressibility models are presented later under geologic processes. Tables 1-9 include the constants, X and Y, for sand and silt (e.g., Hough, 1957, p. 108-109) as well as for kaolinite and a lunar-regolith simulant (Ko, 1971). Rocks are to be considered incompressible.

Adhesion

Adhesion is a function of the properties of both the soil and metal surfaces. Analyses of soillike materials adhering to the collectorhead of the Viking sampler suggest adhesions in the range of 0.9 to 79 Pa (Moore et al., 1977). These adhesions are consistent with analyses of soillike materials in the footpads of the Viking landers, but it was not possible to separate friction between the soil and metal from adhesion (Moore et al., 1987).

Thermal Inertia

Thermal inertia (I) determines how a material will heat and cool in response to solar illumination; I is equal to the square root of the product of thermal conductivity (k), bulk density (rho_b), and specific heat (c), or $(k * rho_b * c)^{-1/2}$. Thermal conductivity (k) is equal to the sum of the conductivity of the pore gas, the conductivity of grains and grain-to-grain contacts, and the radiative conductivity between grains (Wechsler et al., 1972; Jakosky, 1986). Laboratory measurements of conductivities of a variety of materials under Martian conditions of temperature and pressure have been reported (Wechsler and Glaser, 1965; Fountain and West, 1970), applied to Mars (Kieffer et al., 1973, 1977), and treated theoretically (Jakosky, 1986). Importantly, fine, loose, porous materials, like dust, have low thermal conductivities. Large blocks of rock and rock outcrops have high thermal conductivities. The effect of cementation on the thermal conductivity of a granular material is understood only in a qualitative way, but cementation increases grain-to-grain contacts and thermal conductivity. The specific heat (c) of natural materials is commonly near the range of values used here: 0.16 to 0.20 cal/g K (e.g., Kieffer, 1976; Zimbelman, 1986).

Thermal inertias of Mars between about 60° north and 60° south latitude have been estimated by using Viking Orbiter thermal data (Palluconi and Kieffer, 1981; Christensen, 1982, 1983, 1986a,b). These inertias apply to materials from the surface to their thermal skin depths (0.01-0.2 m, depending on the inertia; Jakosky, 1986). The data show that (1) low inertias are found chiefly in the Tharsis-Amazonis regions and Arabia Terra and (2) the frequency distribution of inertias is bimodal with modes near 0.003 and 0.006 cal/cm $s^{1/2}$ K. Jakosky and Haberle (1990) suggested that the reported inertias are too high by as much as 0.002 cal/cm $s^{1/2}$ K, because the atmospheric model previously employed is an approximation; on the basis of their atmospheric model, they suggest that the inertias of dusts become 0.001 instead of 0.003 cal/cm $s^{1/2}$ K and the particle sizes of the dusts become 5 instead of 50 micrometers. It follows that the modes above become 0.001 and 0.004 cal/cm $s^{1/2}$ K, or so. The entire data set on thermal inertias has not been re-analyzed with the new atmospheric model.

Thermal inertias used in tables 3-9 were obtained in a variety of ways. Some were calculated by using laboratory data (Wechsler and Glaser, 1965; Fountain and West, 1970). Those for soillike materials 1 and 2 are re-estimated by using the diagram of Kieffer et al. (1977; e.g., Moore et al., 1987 and Moore and Jakosky, 1989) combined with a downward revision (0.002 cal/cm $s^{1/2}$ K) of the bulk thermal inertias of the two Viking landing sites (Kieffer, 1976; Christensen, 1982) and a reappraisal of the abundances of materials at the Viking landing sites (Moore and Keller, 1990, 1991). The inertia of drift material remains 0.003 cal/cm^2 $s^{1/2}$ K. Thus, the revised thermal inertias are about 0.002 cal/cm^2 $s^{1/2}$ K lower than previous ones (e.g., Moore et al., 1987; Moore and Jakosky, 1989; Arvidson et al., 1989).

Dielectric Constant

Relative dielectric constant or permittivity is the ratio of the dielectric constant of a material and the dielectric constant of vacuum when the magnetic permeability of the material is the same as that of vacuum. As used here, the dielectric constant is related to the normal reflectivity of a natural surface at radio wavelengths by using the Fresnel reflection coefficient (e.g., Tyler et al., 1976). The normal reflectivity is the ratio of power in a radar wave reflected from a planar mirrorlike surface and the power of the radar wave at normal incidence. Porous natural materials, such as loose dust and frothy lava, have low normal reflectivities, small dielectric constants, and small bulk densities, but non-porous, dense rocks have moderate normal reflectivities and large dielectric constants. The relative dielectric constant of vacuum is one.

The model used to calculate the dielectric constants presented here is the same as that in Moore and Jakosky (1989; see Campbell and Ulrichs, 1969), but the equation of Olhoeft and Strangway (1975) yields similar results. Normal reflectivities for Mars were discussed previously, but interpretation of radar echoes from Mars is more complex than presented above (e.g., Moore and Thompson, 1991).

Rather crude estimates of loss tangents are also included in the tables. These loss tangents are based on an appraisal of the data in Campbell and

Ulrichs (1969).

Magnetic Properties

Magnetic susceptibilities given in tables 3-9 were taken from Hargraves et al. (1977; 1978).

DERIVED PROPERTIES

Derived properties can be calculated or estimated from (1) the acceleration of gravity at the surface (about 3.7 m/s^2); (2) material properties such as cohesion, friction angle, bulk density, compressibility, and pore fluid pressures; (3) the topographic configuration of the surface; and (4) the properties of the structures placed on and in the surface materials. Derivation of these properties is the province of engineers schooled in Soil Mechanics and Off-road Locomotion.

Angle of Repose

Angle of repose (slope stability) is a function of (1) surface gravity; (2) material properties such as cohesion, friction angle, bulk density, and pore fluid pressure; and (3) topographic properties of the surface such as relief and slope. Procedures for analyzing slope stability are given in text books on soil mechanics (Terzaghi, 1943; Hough, 1957; Scott, 1963) and in the literature (e.g., Baker and Garber, 1978).

Bearing Strength

Bearing strength or capacity is a function of the surface gravity and material and footing properties. The material properties include cohesion, friction angle, bulk density, and pore fluid pressure. Footing properties include footing size, shape, roughness, and depth. Procedures for calculating bearing strength are given in text books on soil mechanics (Terzaghi, 1943; Hough, 1957; Scott, 1963).

Penetration Resistance

Penetration resistance is a function of (1) surface gravity; (2) surface material properties such as cohesion, friction angle, bulk density, and pore fluids; and (3) penetrator properties such as penetrometer size, shape, mass, and velocity. Analyses of the penetration of the Viking footpads can be found in Moore et al. (1977, 1987), and the effect of surface gravity on penetration into cohesionless sand was examined by Pyrz (1969).

Rutting and Washboarding

Off-road locomotion is a complicated issue (e.g., Costes et al., 1972) that includes rutting and washboarding. However, the performance of vehicles on Mars and alteration of surfaces are a function of (1) surface gravity; (2) surface material properties such as cohesion, friction angle, bulk density, and pore fluid pressure; (3) vehicle characteristics; and (4) topographic properties of the surface such as power spectral density, slope probability distribution, and rock size distribution.

OTHER FACTORS

Surface Gravity

The acceleration of gravity at the surface of Mars is a fundamental parameter used in analyses of the responses of soillike materials to most loads, such as angle of repose, bearing capacity, and lithostatic loads. The surface gravity of Mars is about 3/8-ths that of Earth and, unlike most parameters, well known. Surface gravity at the elevations of the two Viking landing sites is 3.72 and 3.73 m/s^2 (Sieff and Kirk, 1976), but at 25 km-elevation, surface gravity is near 3.69 m/s^2.

Water and Water Ice

Materials laden with water ice will not be addressed here in detail, because the variety of materials presented are sufficiently diverse for preliminary design studies for spacecraft, vehicles, and habitats on Mars. Permafrost or permanently frozen ground (material below the freezing point of water ice) is unquestionable, but the amounts of water ice in the frozen ground are unknown. Clearly, there is water ice at the surface in the polar regions (Farmer et al., 1976; Kieffer et al., 1976; Farmer and Doms; 1979). Amounts of water in the Viking lander samples are poorly known, but about 1 percent can be inferred (Arvidson et al., 1989) from the results of the molecular-analysis experiment (Biemann et al., 1977). The water probably contributes to the cohesion of the soillike materials and dust. Two to five percent adsorbed water are plausible for clay under Martian conditions of temperature and relative humidity (Mooney et al., 1952; Anderson et al., 1978; Moore et al., 1987). Water ice does not appear to affect the physical/mechanical properties of the soillike materials at the Viking landing sites because the amounts are so small. The Lander 2 sampler operations during the winter yielded no evidence for changes in the mechanical properties of crusty to cloddy materials (Moore, unpublished analyses), even though water ice deposited from the atmosphere was present on the surface (Jones et al., 1979; Wall, 1981; Svitek et al., 1990). It is noteworthy that the sampler performed nominally at temperatures of 150 to 180 K in the winter (Crouch, 1979).

Pore Fluid Pressure

Pore fluid pressure can have a profound effect on the response of porous, very fine soillike materials to rapidly applied loads. This effect has been illustrated during full-scale penetration tests of the Viking lander footpad at ambient atmospheric pressures and by reduced-scale footpad-penetration tests at reduced pressures on Earth (Clark, L. V., 1971). The contributions of positive pore pressures of atmospheric CO_2 in drift material to the penetration of footpad 2 of Viking Lander 1 at 2.4 m/s on Mars are unknown. It is clear, however, that the possible role of positive pore fluid pressures should be considered in Earth-based tests and on Mars.

Positive pore fluid pressures of CO_2 may also develop when soillike materials on Mars are humidified (Huguenin et al., 1986). CO_2 adsorption is beyond the scope of this paper, but Zent et al. (1987) presented a factor-of-three model for the amount of CO_2 adsorption on grain surfaces of Martian soillike materials. Apparently, water molecules in sufficient quantities may completely displace adsorbed CO_2.

Heterogeneity

Most natural surface materials, including those of Mars, are heterogeneous. They may be layered or massive, cemented or friable, and, as gravels or breccias, they include fragments of other rock types. Geologic processes, such as erosion, generally produce an upper surface that is areally heterogeneous. Because heterogeneity is site dependent, each site on Mars must be evaluated separately. Layering is exemplified by the Lander 1 site, where dunelike drifts are superposed on a rocky substrate that includes well-cemented soillike materials (Moore et al., 1987), impact crater ejecta, and intact rock units that crop out locally (Binder et al., 1977). Other materials may be present at this site (Sharp and Malin, 1984). Cementation clearly introduces heterogeneity, because the SO_3 contents of the three soillike materials at the Viking lander sites correlate with the overall strength of the materials as shown by the depths of deep holes excavated by the surface samplers (Clark, et al., 1982; Moore et al., 1987). Rocks are included in soillike materials at both sites (Moore et al., 1978; Dale-Bannister et al., 1988). The Lander 2 site is also heterogeneous, because drifts, crusty to cloddy materials, and rocks are present (Mutch et al., 1977; Moore et al., 1987; Moore and Keller, 1990).

Viking Orbiter images show that heterogeneity is the rule on Mars. A good example is the Tharsis region, where fine-grained deposits are superposed on materials of impact craters and lava flows (e.g., Schaber, 1980).

Geologic Processes

To illustrate the possible effects of geologic processes on the mechanical properties of a soillike material, the compressibility equation with values of X and Y for dust (table 1) is assumed to predict the change of void ratio with depth (h) due to the lithostatic load ($rho_b * g * h$). The dust is deposited on the surface with a bulk density of 950 kg/m^3. Friction angles are calculated using the friction coefficient-void ratio equation above. Cohesions are calculated using porosity and the values of A and B for kaolinite (table 1). According to the calculations, the uppermost 0.21 m is composed of dust with a bulk density of 950 kg/m^3, a friction angle near 22°, and a cohesion near 0.4 kPa (table 1). The values of bulk density, friction angle, and cohesion increase with depth because the lithostatic load compresses the dust.

If the uppermost 5.8 m of dust is removed by some geologic process and the dust does not decompress (e.g., Hough, 1957, p. 112) so that the properties of the remaining materials are unchanged, the bulk density at the surface is 1,200 kg/m^3, the friction angle is 32°, and the cohesion is 1.9 kPa (table 1). The properties of the dust at a depth of 5.2 m become the same as those at 11.0 m in table 1. Thus, erosional history will affect the mechanical properties of the dust at the surface of Mars. There are additional factors that could alter the prediction above, such as vibrations (e.g., Hough, 1957, p. 107) induced by seismic accelerations and winds. These vibrations would make the dust denser, increase the cohesion and friction angles, and reduce the compressibilities.

A similar analysis is given for a lunar-regolith simulant (Ko, 1971) to show that significantly different results are obtained with a material that has a significantly different compressibility (table 2). This simulant might be a reasonable analog for some Martian crater ejecta. Comparison of the results of the analyses for the dust and lunar-regolith simulant shows that the dust has much a smaller bulk density and friction angle at the surface than the lunar-regolith simulant, but the cohesion of dust is larger than that of the lunar-regolith simulant (tables 1 and 2). The friction angle, porosity, and void ratio of the dust at a depth of about 11-m are about the same as those of the lunar-regolith simulant at the surface.

Eolian Processes

There are three factors in the eolian-process equation: (1) barriers and cover, (2) erodibility of the materials, and (3) erosivity of the wind (Chepil and Woodruff, 1963). Barriers partition and reduce the wind stresses at the surface; they also cover erodible materials (Marshall, 1971; Gillette and Stockton, 1989). Rocks, ridges, troughs, and non-erodible clods are barriers on Mars. Rocks and non-erodible clods are cover. Erodibility is a measure of the resistance of the materials to erosion by wind. Erodibility is determined by the size, shape, bulk density, and mechanical stability of the structural units of the surface materials (these units include crusts, *in situ* tilelike prisms of cohesive "soil," imbedded rocks, and loose rock or mineral grains and clods). Mechanical stability is determined, in part, by cohesion. Erosivity of the wind is its capacity to erode and is related to the properties of the atmosphere, wind speed, surface roughness height, wind friction speed, particles entrained in the wind, and the mechanical properties of the entrained particles (e.g., Chepil and Woodruff, 1963; Iversen et al., 1976; White, 1979).

Analyses of the factors in the eolian-process equation are beyond the scope of this paper. However, spacecraft on the surface, vehicles, habitations, and mining would (1) present barriers that will alter wind patterns that will, in turn, permit either accumulation or removal of materials, (2) alter the mechanical stabilities of soillike materials by disaggregation or compaction, and (3) alter the erosivity of the wind by creating materials that can be entrained in the wind. The general effects of these factors are chronicled by the observations of the Viking spacecraft on Mars (Jones, et al., 1979; Guinness, et al., 1982; Moore, 1982; Arvidson et al., 1983; Moore, 1985; Moore et al., 1987) and illustrated by engine exhaust erosion during landing (Hutton et al., 1980; Moore et al., 1979, 1987).

The likelihood of storms and strong winds is not known, because Viking Lander 1, which observed Mars for about 3.3 Martian years, witnessed only one local storm that had winds with sufficient erosivity to alter the surface significantly (Moore, 1982; Arvidson et al., 1983; Moore, 1985; Moore et al., 1987). This storm was dubbed the Dust Storm of Sol 1742 (Moore, 1985). The northeasterly winds of this late winter storm removed chiefly soillike materials that had been mined and used to construct piles. A local storm from the west had passed over Lander 1 in a previous late winter, but the winds were not erosive. The standard deviations of pressure variation about the sol mean were about half those of the Sol 1742 storm (e.g., Tillman, 1989).

TABLES OF SELECTED PROPERTIES

Tables 3 through 7 list the physical/mechanical properties of undisturbed materials that are believed to be the most likely to be encountered on Mars: dust, soillike material in crusts and clods, soillike material in blocky clods, sand sheets and dunes, and bedrock and rock fragments. In tables 8 and 9, respectively, are listed the physical/mechanical properties of disturbed dust and blocky soillike material. Values of the properties may differ modestly from those in the references and those that might be offered by others, but they are believed to be reasonable values.

FOUR QUESTIONS

In conclusion, four questions posed at the workshop and my answers to them are given below.

1. What is known with confidence?

a. Some people might expect that the surface materials of the Moon could serve as analogs for the surface materials of Mars. However, the surface materials are vastly different because the Moon has no atmosphere. Water and ice have not been found on the Moon. It has a pervasive, relatively uniform regolith that has been produced over eons by meteor and micrometeor bombardment. Mars, on the other hand, has an atmosphere that not only shields it from small meteor impacts, but also contains water vapor. Mars shows evidence for widespread fluvial processes acting in the past and water vapor in the atmosphere and water in the surface materials are partly responsible for cementation of the soillike materials. Wind and water have sorted and redistributed materials to form deposits of dust, sand, and larger particles.

b. Viking lander observations demonstrate the variety and heterogeneity of surface materials and the geologic processes on Mars that are absent on the Moon. Heterogeniety of relative strengths of the soillike materials is well-illustrated by the depths of deep holes excavated with the sampler in drift (0.23 m deep), crusty to cloddy (0.12 m deep), and blocky (0.09 m deep) materials by using the same procedures; Lander 1 footpad penetrations during landing at 2.4 m/s were 0.16 m in drift and 0.04 m in blocky materials (Moore et al., 1987). Other criteria for heterogeneity of the materials are given by Moore et al. (1982). Unlike lunar surface materials, the abundance of small rock fragments in the soillike materials at the Viking sample fields is small (Moore et al., 1987); drift material appears to be composed solely of fine grains, but blocky material includes some rock fragments and strong millimeter-size grains. The thin tabular crusts at the Lander 2 site do not have a counterpart on the Moon.

2. What are considered to be good estimates?

a. The estimates of the friction angles and bulk densities of crusty to cloddy and blocky materials appear to be good estimates, because they are compatible with data on common terrestrial soils and lunar-regolith simulants. However, the small friction angle and bulk density of drift material are problematical (Moore et al. 1982; 1987).

b. Most materials elsewhere on Mars appear to be similar to common terrestrial soils because the average thermal inertia and radar reflectivity and their correlation are consistent with common terrestrial soils and crusty to cloddy and blocky materials.

3. What is not known?

a. Our knowledge of the variation of relevant physical/mechanical properties across the surface of Mars and, particularly, with depth below the surface is severely limited, because thermal and radar observations represent bulk values for the uppermost surfaces of large areas. Additionally, the Viking landers only sampled the uppermost tens of centimeters in small areas at two places.

b. Lower bound bulk densities and friction angles of dusts on Mars are unknown, because of the uncertainties in the analyses of the Viking lander sampler data on drift material and the analyses of the remote thermal and radar observations.

c. The temporal probability of the occurrence of local dust storms with very strong winds is not known, because only one such storm was observed by the Viking landers during 3.3 Mars years.

4. What key measurements could/should be made in the future?

a. The landing and operation of suitably designed unmanned spacecraft and roving vehicles in various places for reasonably long periods of time will increase our understanding of Martian surfaces, surface materials, and eolian processes many-fold.

b. Returned samples from various places will provide much needed information about Martian surface materials.

CONCLUSION

The surface material parameters presented here are believed to be a fair representation of those of the major materials likely to be encountered on Mars. It may be possible for engineers to design spacecraft that can land on and traverse all of the materials and construct habitats on and in them. If this is not possible, the exploration of Mars is still a viable goal because most of the surface materials on Mars appear to be similar to terrestrial soils and rocks (Moore and Jakosky, 1989).

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Table 1. Compression of a model dust by lithostatic loading on Mars.

Depth [m]	Load [kPa]	Bulk Density [kg/m^3]	Friction Angle [degrees]	Cohesion [kPa]	Porosity [fraction]	Void Ratio [ratio]
0	0	950	22	0.4	0.64	1.8
0.21	0.8	950	22	0.4	0.64	1.8
0.42	1.5	991	24	0.5	0.62	1.6
0.82	3.0	1,040	26	0.6	0.60	1.5
1.6	6.0	1,080	27	0.9	0.58	1.4
3.0	12.0	1,140	29	1.3	0.56	1.3
5.8	24.0	1,200	32	1.9	0.54	1.2
11.0	48.0	1,260	34	2.9	0.52	1.1
21.0	96.0	1,340	37	4.8	0.49	1.0
40.0	190.0	1,420	41	8.4	0.46	0.84
75.0	380.0	1,510	45	16.0	0.42	0.73

Notes. The values for X (17.332) and Y (6.128) used in the compressibility equation and A (10.22) and B (17.71) used in the cohesion equation were estimated by the author from the data of Ko (1971).

The bulk density of disturbed drift material (Clark et al., 1977) and a grain density near 2,610 kg/m^3 yield a porosity near 0.58, but the bulk density of dust that settles to the surface of Mars from the atmosphere may be less than 1,100 kg/m^3. For clay soils on Earth, void ratios in excess of 1.8 appear possible (e.g., Hough, 1957, p. 30-31); a maximum void ratio of 2.0 appears reasonable for the dusts that settle from the atmosphere to the surface of Mars.

Table 2. Compression of a lunar-regolith soil model by lithostatic loading on Mars.

Depth [m]	Load [kPa]	Bulk Density [kg/m^3]	Friction Angle [degrees]	Cohesion [kPa]	Porosity [fraction]	Void Ratio [ratio]
0	0	1,400	32	0.1	0.53	1.1
0.13	0.7	1,480	35	0.2	0.51	1.0
0.25	1.4	1,510	36	0.2	0.50	1.0
0.99	5.6	1,550	38	0.2	0.48	0.9
1.9	11.2	1,580	39	0.3	0.47	0.9
3.8	22.0	1,600	40	0.3	0.47	0.9
7.5	45.0	1,630	41	0.4	0.46	0.8
15.0	89.0	1,660	43	0.4	0.45	0.8
29.0	178.0	1,685	44	0.5	0.44	0.8

Notes. The values for X (30.04) and Y (22.98) used in the compressibility equation and A (7.092) and B (17.71) used in the cohesion equation were estimated by the author from the data of Ko (1971) and Mitchell et al., (1972), respectively. The assumed grain density was about 3,000 kg/m^3. A maximum void ratio of 1.1 is reasonable.

Table 3. Physical/mechanical properties of dust on Mars. Drift material at the Lander 1 site is an analog for the dust.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 10	Moore & Jakosky, 1989
Clod size	(meters)	thin, weak crusts	
Rock fragments	(meters)	none	
Grain hardness	(Mohs' scale)	1 - 3	Winchell & Winchell, 1956; clays
Density			
Grain density	(kg/m^3)	2,610	Winchell & Winchell, 1956; clays
Bulk density	(kg/m^3)	1,000 $\pm$ 150	A guess from friction angle model
Porosity	(fraction)	0.62	Nominal; calculated
Void ratio	(dimensionless)	1.6	Nominal; calculated
Friction Angle (surface)	(degrees)	18.0 $\pm$ 2.4	Moore & Jakosky, 1989 Moore et al., 1982, 1987
Cohesion (surface)	(kPa)	1.6 $\pm$ 1.2	Moore & Jakosky, 1989
range		0 - 3.7	Moore et al., 1982, 1987
A		10.22	Ko, 1971; kaolinite
B		17.71	
Adhesion	(Pa)	0.9 - 79	Moore et al., 1977; 1987
Compressibility	(Pa)		
X		17.332	Ko, 1971; kaolinite
Y		6.128	
Thermal			
Conductivity	(10^{-5} cal/s cm K)	0.5 - 6.0	Wechsler & Glaser, 1965
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	1.0	Assumed for calculations
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	1 - 3	Calculated
Electrical			
Relative dielectric constant	(dimensionless)	1.8 - 2.3	Campbell & Ulrichs, 1969 Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.003-0.005	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility	(10^{-4} G cm^3/g Oe)	4 - 30	Hargraves et al., 1977

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Dusts on the Martian surface may be superposed on a variety of substrates that include bedrock and cohesive soillike materials. At the Lander 1 site, drift material is superposed on a rocky substrate that includes soillike blocky material, crater ejecta, and bedrock units that locally crop out.

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) may be important because positive pore pressures develop when dusts are rapidly loaded. Adsorbed gases may be liberated when dusts are moistened with water. About 1 percent water is probably adsorbed.

Friction angle. Model friction angle is 24° $\pm$ 5°.

Cohesion. Cohesion partly due to very weak cementation at surface. Weakly cohesive dust has a consistency somewhat like that of kitchen flour.

Compressibility. Maximum void ratio is about 2.0 (eg., Hough, 1957, p. 30-31) and minimum is uncertain.

Table 4. Physical/mechanical properties of soillike material 1 on Mars. Crusty to cloddy material at the Lander 2 site is an analog for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 10	Moore & Jakosky, 1989
Clod size	(meters)	0.001 - 0.04	Moore et al., 1987
Rock fragments	(meters)	0.035 (rare)	Moore et al., 1987
Grain hardness	(Mohs' scale)	1 - 3	Winchell & Winchell, 1956; clays
Density			
Grain density	(kg/m^3)	2,610	Winchell & Winchell, 1956; clays
Bulk density	(kg/m^3)	1,400 $\pm$ 200	Moore et al., 1987
Porosity	(fraction)	0.46	Nominal; calculated
Void ratio	(dimensionless)	0.86	Nominal; calculated
Friction Angle (surface)	(degrees)	34.5 $\pm$ 4.7	Moore & Jakosky, 1989 Moore et al., 1982, 1987
Cohesion (surface)	(kPa)	1.1 $\pm$ 0.8	Moore & Jakosky, 1989
range		0 - 3.2	Moore et al., 1982, 1987
A		10.22	Ko, 1971; kaolinite
B		17.71	
Adhesion	(Pa)	0.9 - 79	Moore et al., 1977; 1987
Compressibility	(Pa)		
X		17.332	Ko, 1971; kaolinite
Y		6.128	
Thermal			
Conductivity	(10^{-5} cal/s cm K)	3 - 29	Calculated
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	1.4	Assumed for calculations
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	3 - 8	Estimated, see text
Electrical			
Relative dielectric constant	(dimensionless)	2.4 - 3.3	Campbell & Ulrichs, 1969 Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.005-0.007	A guess; Campbell & Ulrichs
Magnetic			
Susceptibility	(10^{-4} G cm^3/g Oe)	4 - 30	Hargraves et al., 1977

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Soillike material on the Martian surface may be superposed on a variety of substrates that include bedrock, crater ejecta, and cohesive soillike materials. At the Lander 2 site, crusty to cloddy material may consist of a fine component of ejecta from the impact crater Mie admixed with local materials; local materials dominate (Moore et al., 1987).

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) may be important because positive pore pressures develop when fine-grained materials are rapidly loaded. Adsorbed gases may be liberated when soillike materials are moistened with water. About 1 percent water is probably adsorbed.

Cohesion. Cohesion partly due to weak cementation of material near surface. Crusts can be easily disaggregated with finger pressure.

Compressibility. Maximum void ratio is about 2.0 (e.g., Hough, 1957, p. 30-31) and minimum is uncertain.

Table 5. Physical/mechanical properties of soillike material 2 on Mars. Blocky material at the Lander 1 site is an analog for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 1,000	Arvidson et al., 1989
Clod size	(meters)	0.001 - 0.04	Moore et al, 1987
Rock fragments	(meters)	0.001 - 0.035	Dale-Bannister, 1988
Grain hardness	(Mohs' scale)	1 - 7	Winchell & Winchell, 1956; clays, pyroxene, olivine
Density			
Grain density	(kg/m^3)	2,610 - 3,000	Winchell & Winchell, 1956; clays
Bulk density	(kg/m^3)	1,600 $\pm$ 400	Moore et al., 1987
Porosity	(fraction)	0.39	Nominal; calculated
Void ratio	(dimensionless)	0.63	Nominal; calculated
Friction Angle (surface)	(degrees)	30.8 $\pm$ 2.4	Moore & Jakosky, 1989; Moore et al., 1982, 1987
Cohesion (surface)	(kPa)	5.5 $\pm$ 2.7	Moore & Jakosky, 1989
range		2.2 - 10.6	Moore et al., 1982, 1987
A		8.63	A guess
B		17.71	
Adhesion	(Pa)	0.9 - 79	Moore et al., 1985; 1977
Compressibility	(Pa)		
X		24.122	A guess, but like silt
Y		11.964	Hough, 1957
Thermal			
Conductivity	(10^{-5} cal/s cm K)	8 - 39	Calculated
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^2)	1.6	Assumed for calculations
Inertia	(10^{-3} cal/cm^2 $s^{1/2}$ K)	5 - 10	Estimated, see text
Electrical			
Relative dielectric constant	(dimensionless)	2.4 - 4.5	Campbell & Ulrichs, 1969; Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.005-0.010	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility	(10^{-4} G cm^3/g Oe)	4 - 30	Hargraves et al., 1977

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Soillike material on the Martian surface may be superposed on a variety of substrates that include bedrock, crater ejecta, and cohesive soillike materials. At the Lander 1 site, blocky material is superposed on and admixed with crater ejecta; it is superposed on rock units which locally crop out.

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) are probably unimportant because of the large cohesion due to cementation. Adsorbed gases may be liberated when soillike materials are moistened with water. About 1 percent water may be adsorbed.

Cohesion. Cohesion chiefly due to moderate cementation of material near surface. Material is like garden soil and clods can be easily disaggregated by hand.

Compressibility. Maximum void ratio is about 1.6 and minimum void ratio is about 0.4 (Hough, 1957, p. 30-31).

Table 6. Physical/mechanical properties of sand sheets and dunes on Mars. Terrestrial sand is an analog for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	100 - 250	Iversen et al., 1976; dunes
Grain size	(micrometers)	250 - 1,000	Christensen, 1983; sand sheets
Rock fragments	(meters)	na	
Grain hardness	(Mohs' scale)	5 - 7	Winchell & Winchell, 1956; pyroxene & olivine
Density			
Grain density	(kg/m^3)	2,800 ± 200	A guess
Bulk density	(kg/m^3)	1,700 ± 175	Seed & Goodman, 1964
Porosity	(fraction)	0.39	Nominal; calculated
Void ratio	(dimensionless)	0.6	Nominal; calculated
Friction Angle (surface)	(degrees)	38.0 ± 4.0	Hough, 1957 Seed & Goodman, 1964
Cohesion (surface)	(kPa)	0	Little or no change with depth if uncemented; see below
Adhesion	(Pa)	0.9 - 79	Moore et al., 1977, 1987
Compressibility	(Pa)		
X		29.507	A guess, but like loose sand
Y		25.424	Hough, 1957
Thermal			
Conductivity	(10^{-5} cal/s cm K)	5 - 37	Calculated; sand - sand sheet
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	1.7	assumed for calculation
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	4 - 10	Kieffer, et al, 1973 Jakosky, 1986
Electrical			
Relative dielectric constant	(dimensionless)	3.3 - 4.0	Campbell & Ulrichs, 1969 Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.007-0.009	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility		---	

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Sands and sand dunes on the Martian surface may be superposed on a variety of substrates that include bedrock, crater ejecta, and cohesive soillike materials.

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) is probably unimportant for most engineering purposes because of large permeability and small compressibility.

Angle of repose. 38.0 ± 4.0 degrees, if uncemented.

Cohesion. Sand has a shear strength intercept that is a function of grain size (Goodman and Seed, 1963) that may or may not affect material processing. See also: Klein and White, 1990.

Thermal Inertia. Reported inertias of intercrater deposits are 8 to 12 (Christensen, 1983), which become 6 to 10 when revised downward (Jakosky and Haberle, 1990). If the deposits are not cemented, grain sizes could range from 250 micrometers to several centimeters (Jakosky, 1986) and conductivities from 11 to 37.

Eolian processes. If uncemented, cohesionless sands are erodible so that strong winds may produce sand storms.

Table 7. Physical/mechanical properties of bedrock and rock fragments on Mars. Terrestrial rocks are analogs for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 10,000	Moore et al., 1987; 1978 Binder et al., 1977
Rock fragments	(meters)	0.001 - 5	Moore et al., 1987
Grain hardness	(Mohs' scale)	5 - 7	Winchell & Winchell, 1956 pyroxene & olivine
Density			
Grain density	(kg/m^3)	2,600 - 3,000	Common knowledge
Bulk density	(kg/m^3)	2,500 - 2,900	Common knowledge
Porosity	(fraction)	small	
Void ratio	(dimensionless)	small	
Friction Angle	(degrees)	40 - 60	Common knowledge
Cohesion	(kPa)		
range		10^3 - 10^4	Common knowledge
Adhesion	(Pa)	na	
Compressibility	(Pa)	incompressible	
Thermal			
Conductivity	(10^{-5} cal/s cm K)	300 - 580	Calculated
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	2.7	Assumed for calculation
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	40 - 50	Wechsler & Glaser; 1965
Electrical			
Relative dielectric constant	(dimensionless)	7 - 9	Campbell & Ulrichs, 1969 Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.015-0.020	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility		---	

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Rock may be present as fragments and blocks on and near the surface, as outcrops at the surface, and as bedrock covered in places by soillike units.

Pore fluids. Pore fluids are unimportant for most engineering purposes because of large cohesion and low porosities.

Rubble Size (a model). In general, size-frequency and size-area distributions for rocks on Mars are unknown. In lieu of data, the following distribution is suggested for rocks larger than 0.1 m:

$$N = k * D^a,$$

where N is the cumulative number of rocks per square meter with diameters larger than D (in meters), k is a parameter that varies with location, and a is near (-)2.66. For this distribution, the cumulative fraction of area (A) covered by circular rocks is:

$$A = c * D^{-0.66},$$

where c is a parameter that varies with location (see Christensen, 1986a,b) . Suggested values for c are:

0.0022	Rock poor surface (Tharsis-Arabia)
0.0131	Nominal surface (Modal Mars)
0.0656	Very rocky surface (Crater ejecta)
0.0408	Viking Lander 2 site (Northern plains).
******	There is a continuum of c values.

Table 8. Physical/mechanical properties of disturbed dust on Mars. Disturbed drift material at the Lander 1 site is an analog for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 10	Moore & Jakosky, 1989
Clod size	(meters)	weak lumps	Moore et al., 1982, 1987
Rock fragments	(meters)	none	Moore et al., 1987
Grain hardness	(Mohs' scale)	1 - 3	Winchell & Winchell, 1956; clays
Density			
Grain density	(kg/m^3)	2,610	Winchell & Winchell, 1956; clays
Bulk density	(kg/m^3)	1,100 $\pm$ 150	Clark et al., 1977
Porosity	(fraction)	0.58	Nominal; calculated
Void ratio	(dimensionless)	1.4	Nominal; calculated
Friction Angle (surface)	(degrees)	18.0 $\pm$ 2.4	Assumed same as dust
Cohesion	(kPa)	0.03 $\pm$ 0.02	Moore et al., 1987
range		0 - 0.05	
A		10.22	Ko, 1971; kaolinite
B		17.71	
Adhesion	(Pa)	0.9 - 79	Moore et al., 1977; 1987
Compressibility	(Pa)		
X		17.332	Ko, 1971; kaolinite
Y		6.128	
Thermal			
Conductivity	(10^{-5} cal/s cm K)	0.5 - 3.0	Wechsler & Glaser, 1965
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	1.0	Assumed for calculations
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	1 - 2	Calculated
Electrical			
Relative dielectric constant	(dimensionless)	1.8 - 2.0	Campbell & Ulrichs, 1969 Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.003-0.004	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility	(10^{-4} G cm^3/g Oe)	4 - 30	Hargraves et al., 1977

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Disturbed dusts are superposed on a variety of substrates. At the Lander 1 site, disturbed drift material is superposed on all materials, including the spacecraft.

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) may be important because positive pore pressures develop when dusts are rapidly loaded. Adsorbed gases may be liberated when dusts are moistened with water. About 1 percent of water is probably adsorbed.

Friction angle. Model friction angle is 28° $\pm$ 6°.

Cohesion. Cohesion reduced by disaggregation and increased by compaction.

Compressibility. See table 3.

Eolian processes. Disturbances made by the spacecraft during landing, by vehicles driving across the surface, by mining activities, and by processing will alter the mechanical stabilities of soillike materials. Erodibilities of the soillike materials may be increased or decreased depending on a variety of factors.

Table 9. Physical/mechanical properties of disturbed soillike material 2 on Mars. Disturbed blocky material at the Lander 1 site is an analog for this material.

PROPERTY NAME	PROPERTY UNITS	PROPERTY VALUES	REFERENCES AND COMMENTS
Grains and clods			
Grain size	(micrometers)	0.1 - 1,000	Arvidson et al., 1989
Clod size	(meters)	0.001 - 0.04	Moore et al, 1987
Rock fragments	(meters)	0.001 - 0.035	Dale-Bannister, 1988
Grain hardness	(Mohs' scale)	1 - 7	Winchell & Winchell, 1956; clays, pyroxene, olivine
Density			
Grain density	(kg/m^3)	1,100 - 3,000	Includes clods
Bulk density	(kg/m^3)	1,000 $\pm$ 200	A guess
Porosity	(fraction)	0.4	Nominal; calculated
Void ratio	(dimensionless)	0.6	Nominal; calculated
Friction Angle (surface)	(degrees)	30.8 $\pm$ 2.4	Assumed to be like soillike material 2
Cohesion (surface)	(kPa)	0.03 $\pm$ 0.03	Moore & Jakosky, 1989
range		0 - 0.06	Moore et al., 1987
A		8.63	A guess; like silt
B		17.71	Hough, 1957
Adhesion	(Pa)	0.9 - 79	Moore et al., 1985; 1977
Compressibility	(Pa)		
X		24.122	A guess; like silt
Y		11.964	Hough, 1957
Thermal			
Conductivity	(10^{-5} cal/s cm K)	8 - 39	Estimated; blocky material
Specific heat	(cal/g K)	0.16 - 0.20	Kieffer, 1976; Zimbelman, 1986
Bulk density	(g/cm^3)	1.0	Assumed for calculations
Inertia	(10^{-3} cal/cm^2 s$^{1/2}$ K)	4 - 8	Calculated
Electrical			
Relative dielectric constant	(dimensionless)	1.8 - 2.5	Campbell & Ulrichs, 1969; Moore & Jakosky, 1989
Loss tangent	(dimensionless)	0.003-0.005	A guess; Campbell & Ulrichs, 1969
Magnetic			
Susceptibility	(10^{-4} G cm^3/g Oe)	4 - 30	Hargraves et al., 1977

GEOLOGIC NARRATIVE AND GENERAL COMMENTS

Heterogeneity. Disturbed soillike materials are superposed on a variety of substrates. At the Lander 1 site, disturbed blocky material is superposed on all materials, including the spacecraft.

Pore fluids. CO_2 at ambient pressures (about 680 - 1,020 Pa) is probably unimportant because of the large cohesion due to cementation. Adsorbed gases may be liberated when dusts are moisten with water. About 1 percent water is probably adsorbed.

Cohesion. Cohesion reduced by disaggregation.

Compressibility. See table 5.

Eolian processes. Disturbances made by the spacecraft during landing, by vehicles driving across the surface, by mining activities, and by processing will alter the mechanical stabilities of soillike materials. Erodibilities of the soillike materials may be increased or decreased depending on a variety of factors.