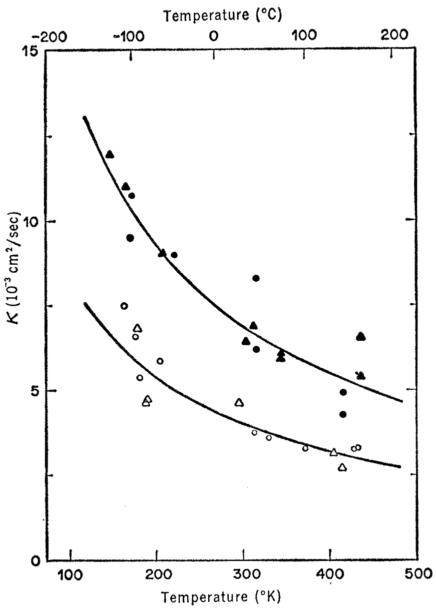

Fig. 1. Thermal diffusivity plotted against temperature for Apollo 11 lunar materials. Closed circles, sample 10020; closed triangles, 10057 (type A). Open circles, 10046; open triangles, 10065 (type C).

siderable porosity (*7*) should exhibit lower thermal diffusivities. An even lower thermal diffusivity is to be expected for the lunar soil, type D material.

The equatorial lunar surface temperature is known to vary about 150°C in amplitude with a period of 2.5×10^6 sec. The measurement of heat flow from the interior of the moon in a shallow borehole, nominally 3 m, expected on Apollo 13 (*8*) depends on a rapid decrease of amplitude of the diurnal wave. For lunar material with thermal diffusivities as high as those found for rocks in air in this investigation, 0.75 and 0.45 $\times 10^{-3}$ cm²/sec, corresponding respectively to the materials of type A and type C, the characteristic depths (*9*) for the diurnal wave are 120 and 155 cm. In Table 1, the depths below the flat lunar surface at which the amplitude of the diurnal variation of temperature, 150°C, becomes 10°C, 1°C, and 0.1°C are shown. Almost surely our values may be taken as upper limits for the diffusivity of lunar surface material, and a reliable thermal gradient for heat-flow determination may be measured in a 3-m hole. However, the presence of boulders scattered through the lunar soil of very low diffusivity may prove to be troublesome.

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4. Modal analysis of sample 10020 shows (600 points counted) pyroxene, 43.6 percent; ilmenite, 26.5 percent; plagioclase, 23.6 percent; olivine, 3.7 percent; void, 1.7 percent; and other, 0.7 percent. The sample 10046 shows (1571 points counted) pyroxene, 16.8 percent; opaques, 8.6 percent; plagioclase, 4.7 percent; unidentified, 3.5 percent; glass, 2.9 percent; and matrix (<40 μm), 63.5 percent. In calculating the heat capacity of sample 10046, we approximated the opaques by ilmenite and the matrix by 30 percent glass, 55 percent pyroxene, and 15 percent plagioclase.
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7. Porosity of sample 10057, obtained from the point count of cavities on the surfaces of the sample, is 0.174. (see H. Kanamori, A Nur, O. Chung, D. Wones, G. Simmons, *Science*, this issue.)
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9. The characteristic depth given by $2\pi/\sqrt{\omega/2\kappa}$ is the distance at which the amplitude of a periodic temperature variation with frequency ω is reduced by a factor of exp $(-2\pi)=0.0019$.
10. Supported by NASA contract NAS9-8102.

4 January 1970

Compressibilities of Lunar Crystalline Rock, Microbreccia, and Fines to 40 Kilobars

Abstract. *The compressibilities of three lunar samples were studied at room temperature from 0 to 40 kilobars. The samples were a fine-grained vesicular crystalline rock (type A), a microbreccia (type C), and fines (type D). All samples were porous. The microbreccia and fines were quite compressible at all pressures; the compressibility of the crystalline rock was somewhat less, being 8.4 megabar*$^{-1}$ *at 1 atmosphere and 1.5 megabar*$^{-1}$ *at 35 kilobars. Some porosity appeared to remain in the samples at all pressures. Thus the pressure-volume data derived from these samples may be representative of porous surface and near-surface material in the vicinity of the Apollo 11 landing site but may not be representative of lunar material at depth.*

The pressure-volume properties of three lunar materials were studied to 40 kb at room temperature. These materials were sample 10017,69, a fine-grained vesicular crystalline rock (type A): sample 10048,52, a microbreccia (type C), and sample 10084,78, fines (type D). The method consisted of measuring bulk volume changes under nearly hydrostatic pressure (*1*). If any of the samples can be considered to be representative of lunar material at depth, the pressure-volume data will be useful in calculating lunar density as a function of radius. The data can also be used to perform numerical calculations of meteoritic impact processes. Finally, they provide basic information on the lunar surface material such as compressibility and porosity, and qualita-

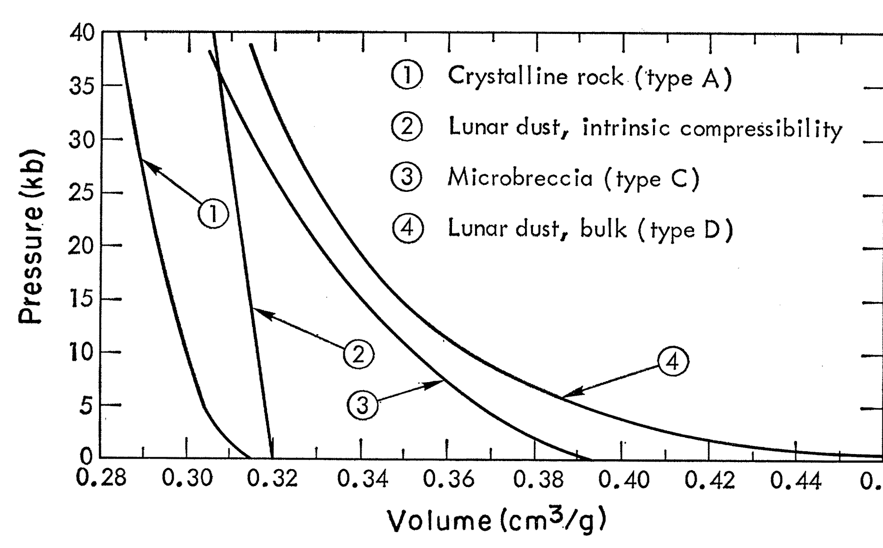

Fig. 1. Pressure versus specific volume for lunar materials.

tive information about the strength of the constitutive minerals can be inferred.

Compressibilities (Fig. 1) of these materials are typical of porous terrestrial rocks (*1*). For example, the change in volume of the crystalline type A rock (Fig. 1, curve 1) is 9.8 percent at 40 kb, which is similar to that of many terrestrial igneous rocks. This sample contained more than 5 percent initial porosity, and some porosity was present at the highest pressures. The compressibility at 35 kb was 1.5 Mb^{-1}, which is much higher than intrinsic compressibilities calculated at this pressure for a plagioclase-clinopyroxene-ilmenite rock of reported composition (*2*). These are estimated to be about 0.9 Mb^{-1} at 35 kb. The higher compressibility of the lunar rock is due to residual porosity.

If near-surface lunar rock is similar to this crystalline rock, one can predict P-wave velocities near the lunar surface. If one assumes a Poisson's ratio of 0.25 and uses the initial compressibility of 8.43 Mb^{-1}, the predicted velocity of P-waves is 2.6 km/sec.

The lunar dust is much more compressible, as would be expected for an unconsolidated powder (Fig. 1, curve 4). The intrinsic compressibility for the fine dust (Fig. 1, curve 3) was determined by mixing equal volumes of dust and tin powder; the mixture was hot-pressed to remove all porosity. After correcting for the effects of tin, we obtained the intrinsic pressure-volume curve of the dust which can be represented by $-\Delta V/V_0 = ap - bp^2$ with $a = 1.28$ Mb^{-1}, $b = 5.5$ Mb^{-2}, and $V_0 = 0.3197$ cm^3/g. Note that some porosity remains in the dust even at 38 kb, as is also the case for quartz-feldspar sands and gravels (*3*). The strength of the individual lunar dust minerals and glasses thus seems to be of the same order of magnitude [40 to 50 kb at a confining pressure of 30 kb (*4*)] as quartz and feldspars.

The microbreccia (type C) rock is also very compressible at all pressures (Fig. 1, curve 3), and it is certainly not a well-compacted rock. Its compressibility is 17 Mb^{-1} at 1 atm and 3.6 Mb^{-1} at 35 kb.

Inelastic effects were noted in all three lunar materials. Some of the porosity was permanently removed upon unloading to 1 atm; these were 4.5 percent for the crystalline rock, 12.8 percent for the microbreccia and 27 percent for the fines. However, at low pressure some porosity was recovered, as is also the case for porous terrestrial igneous rocks (*1, 3*).

In conclusion, all the samples, including the crystalline rock, contained porosity up to pressures of 40 kb. The samples may be representative of surface and near-surface material in the vicinity of Tranquillity Base. If the lunar interior is hot, one would not expect porous rock to be present at high pressures and temperatures, and in that case the lunar crystalline rock, for example, could not be used as a model for interior material. However, if the moon is cold, then a porous rock such as the crystalline rock may be a model for at least part of the lunar interior. Data for lunar rocks from many sites must be obtained to construct a reasonable model of the interior of the moon.

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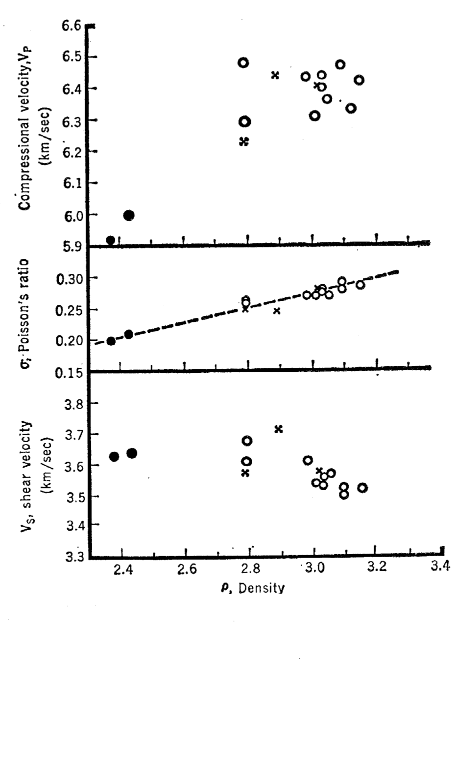
4 January 1970

Sound Velocity and Compressibility for Lunar Rocks 17 and 46 and for Glass Spheres from the Lunar Soil

Abstract. *Four experiments on lunar materials are reported: (i) resonance on glass spheres from the soil; (ii) compressibility of rock 10017; (iii) sound velocities of rocks 10046 and 10017; (iv) sound velocity of the lunar fines. The data overlap and are mutually consistent. The glass beads and rock 10017 have mechanical properties which correspond to terrestrial materials. Results of (iv) are consistent with low seismic travel times in the lunar maria. Results of analysis of the microbreccia (10046) agreed with the soil during the first pressure cycle, but after overpressure the rock changed, and it then resembled rock 10017. Three models of the lunar surface were constructed giving density and velocity profiles.*

Glass Spheres. Sound velocities and Poisson's ratio, σ, of glass spheres from the lunar soil (300 to 600 μm diameter) were measured with the resonance sphere technique (*1*). Densities were measured using heavy liquids and also by measuring volume and mass. The results are shown in Fig. 1, along with data of tektites (*1*), and some artificial lunar glasses (*2*) with composition close to the lunar soil. Glass spheres with low density are colorless or lightly colored and may have low TiO_2 and FeO content; high density glass is dark brown, red or black, and may contain large amounts of TiO_2 and FeO.



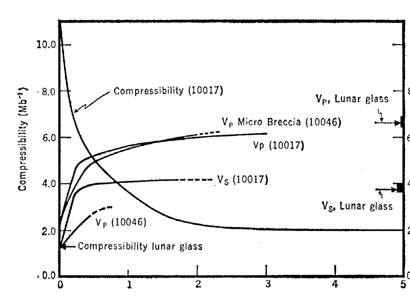


Fig. 1 (left). Sound velocities and Poisson ratio for ten lunar soil glass spheres, two tektites and three artificial glass spheres, whose composition is similar to Apollo 11 lunar soil and rocks. Solid circles, lunar glass; open circles, tektite; crosses, pseudo lunar glass. Fig. 2 (above). A composite of pressure data showing β of rock 10017, V_P and V_S for rock 10017, V_P for the microbreccia 10046 (first run and final run), and V_P, V_S, and β for the glass spheres.