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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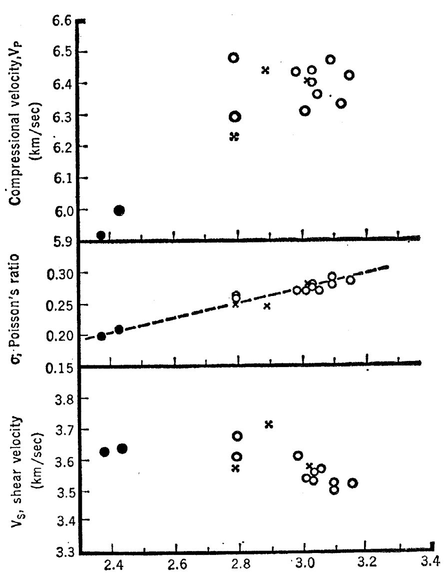
4 January 1970

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.



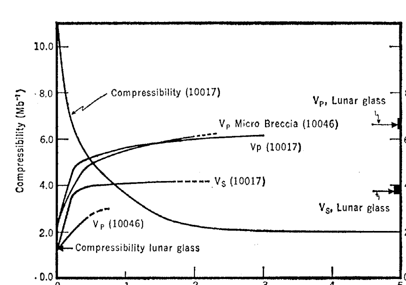


Fig. 1 (left). Sound velocities and Poisson ratio for ten lunar soil glass spheres, two tektites and three artificial glass spheres, whose composition is similar to Apollo 11 lunar soil and rocks. Solid circles, lunar glass; open circles, tektite; crosses, pseudo lunar glass. Fig. 2 (above). A composite 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.

Although the density ranges from 2.79 to 3.15, the compressional velocity, V_P, remains about the same, while the shear velocity changes slightly. This is consistent with the known fact that the density of rocks and minerals, but not the velocity, increases with the addition of Fe and Ti. This is also true of the artificial lunar glass. There seems to be a useful correlation, showing that σ increases with ρ from sample to sample; σ may be an indicator of Ti and Fe content. We anticipate a correlation between σ and the index of refraction. We wondered if values of V_S and V_P for lunar glass could be considered as typical of lunar rocks in an idealized state (no porosity or cracks). We applied the fourth-power relationship between the moduli and the density for minerals and glasses (*3*). The assumption of a smaller volume (95 percent) for the idealized crystal, with no shift in bulk modulus and a slight shift in shear modulus, leads us to conclude that V_P for the idealized Apollo 11 lunar rock is 6.5 to 7.0 km/sec at P=0, with V_S about 4 km/sec.

The Debye temperature of the glass beads is about 530, computed from V_P and V_S. The data from the glass beads indicate they are not like tektites, although it may turn out that they resemble microtektites (*4*).

Compressibility. Static compressibility of the fine grained vesicular rock 10017 was measured using the strain gage method of Brace (*5*). Measurements of linear compressibility were made in three perpendicular directions at pressures up to 2 kbar and in one direction to 6 kbar. The volume compressibility, β, is typical of that observed for many terrestrial rocks; it decreases rapidly with pressure from a very high value within a kilobar (Fig. 2). This effect is due to the closing of cracks (*5*, *6*).

Above 0.5 kbar, linear compressibility is nearly isotropic, indicating little preferred orientation of minerals. Below that pressure, however, some anisotropy was found, which suggests a preferred orientation of cracks. Such a preferred orientation could have been produced by a variety of mechanisms, and in particular by impact or thermal shock.

The value of β at high pressure is surprisingly high, closer to acidic than to basic igneous rocks (*6*). At 5 kbar β is 1.98 Mb^{-1} and decreases steadily with P. This high value is probably due to porosity associated with nearly spherical vesicles, which will affect β even at very high pressures [since they are not readily closed (*7*)]. An estimate of the intrinsic

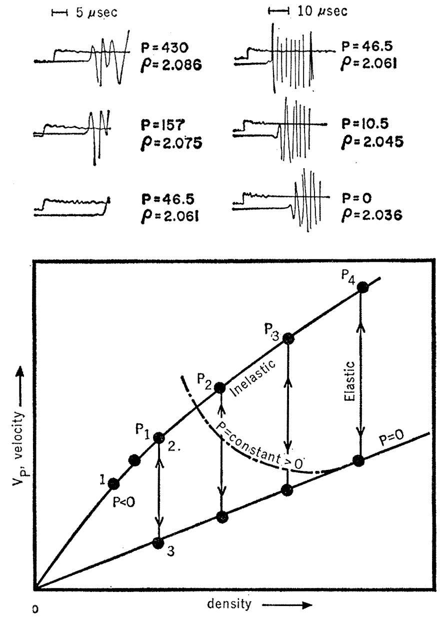


Fig. 3. V_P, compressional velocity of the lunar soil. The top curve is inelastic compression; the bottom curve the extrapolated value of V_P plotted against ρ at P=0; the straight lines, the loci of elastic compressions with P, from different porosity states; the dashed lines, curves of constant P. Typical arrival time patterns are traced above the curve.

β, calculated from the results on the glass beads, is indicated in Fig. 2.

Thus, the presence of open cracks explains the high β and low V_P of 10017 and 10046 near P=0. This argument also may explain the low velocities inferred from the LEM impact (*8*), during the Apollo 12 seismic experiment. Because of the low gravity, open cracks (and their effects) will reach to far greater depths on the moon than on earth. Furthermore, the anomalous low velocities observed at low pressure are not observed on earth, because the cracks are filled with water (*9*). On the moon, however, because water is probably not present, *in situ* velocities in the upper 20 km can be expected to be low compared to the intrinsic values of rocks.

Sound Velocities of Rocks 10017 and 10046. The sound velocity of rocks 10017 and 10046 (a microbreccia) was measured versus pressure with a modified Birch technique (*10*, *11*). The data obtained are relative changes in the acoustic delay time. These, together with the sound velocities measured at ambient pressure (V_P=1.84 km/sec for 10017, 1.2 km/sec for 10046) were used to compute the velocity pressure curves shown in Fig. 2. The shear velocity was calculated from the V_P and β data.

For each sample, we found a sharp increase in velocity with applied pressure. The initial run on the microbreccia yielded the smallest initial rate of change of velocity and the final value of V_P at high P was about 3 km/sec. After pressure cycling to 7 kbar, in a subsequent run V_P increased faster with P and attained a value at high P double that in the initial run and became similar to that of rock 10017. The initial slope, however, remains less than for rock 10017. The change is most likely due to alteration of the pore structure by pressure. We feel, therefore, that in the initial run on 10046 the effect of equant pores dominated both the change in velocity and the final velocity at high P. After cycling through 7 kbar, the microstructure was irreversibly altered, and cracks developed at the expense of

Table 1. Three models of the velocity profile of the upper surface of the lunar maria. Compressional velocity, V_P; shear velocity, V_S (km/sec). Density, ρ (g/cm³). Depth below surface, Z (km). Three models corresponding to lunar soil (1), broken rock (2), and solid rock (3).

Property	Pressure (kbar)					
	0	0.05	0.1	0.5	1.0	1.5
			Number 1			
ρ	2.20	2.21	2.22	2.23	2.24	2.25
V_P	1.07	1.20	1.40	2.06	2.65	3.20
V_S	0.67	0.73	0.80	1.08	1.44	1.75
Z	0.0	1.5	2.8	13.7	27.2	39.3
			Number 2			
ρ	3.10	3.10	3.11	3.12	3.15	3.17
V_P	1.81	1.89	1.97	2.46	2.98	3.38
V_S	1.01	1.05	1.10	1.38	1.67	1.89
Z	0.0	1.0	2.0	9.8	19.5	29.0
			Number 3			
ρ*	3.10	3.10	3.10	3.10	3.10	3.10*
V_P	1.80	2.55	3.30	5.20	5.60	5.80
V_S	1.20	1.75	2.30	3.90	4.10	4.12
Z	0.0	1.0	2.0	9.9	19.6	29.0

*Density does not change because only thin cracks are closing.

equant pores. This is evidenced by the facts that: (i) the velocity at P=0 changed from an initial value of 1.2 to 2.2 km/sec, with little change in density; (ii) the final V_P-P curve is similar to that of rock 10017. Because of the presence of many equant pores, it is unlikely that V_P of about 6 km/sec represents the intrinsic values for these rocks. The idealized rock should have a higher value, perhaps closer to that of the glass spheres.

V_P of Lunar Fines. Compressional sound velocities were measured at various pressures and compactness on the soil, by a technique (*12*) that incorporates the pulse transmission method (*11*). Sample length and density were determined throughout the experiment.

Behavior of V_P, as a function of compaction (density), is shown schematically in Fig. 3. The soil compacts inelastically, along the locus P_1-P_4. If at point 2 pressure is released, the density changes very little, but V_P drops elastically (point 2, to point 3 at P=0).

The line marked "P=0" represents the locus of values of V_P (ρ, P=0) generated by a series of elastic and inelastic pressure cycles. Curves of constant pressure (P > 0) have the general shape shown by the dashed line. For the soil along an elastic curve V_P drops from 2.23 (ρ=2.08, P=430 bars) to 0.67 km/sec (ρ=2.03, P=0).

For P=0, V_P increases with ρ along the zero isobar, and importantly, has a value of 1.1 km/sec at ρ=2.2 comparable to the zero pressure values of the microbreccia rock 10046 (V_P=1.2, ρ=2.2). From the observed $\Delta P/\Delta\rho$ along the elastic curve, the bulk modulus, K, of the lunar soil is found. Significantly at P=0, the value of K for the soil and 10046 are close (12 kbar and 19 kbar, respectively). The soil and microbreccia are mechanically similar.

The Velocity Profile in the Lunar Surface. Three simple models were calculated from our data giving velocity versus pressure at shallow lunar depth (Table 1). Model 1 assumes a soil-microbreccia mixture under self-compaction. Model 2 assumes a breccia of "igneous" rock 10017 under self-compaction. The variation of K with P as measured for the soil and 10046 (first pressure run) is used. However zero pressure values of V_P, ρ, and K are taken from 10017. This "igneous heterogeneous" model corresponds to a regolith of brecciated and broken up rock blocks.

Model 3 is derived from V_P and β of the rock 10017 and represents the case of a homogenous half space, in which cracks simply close under pressure. All three are dry models, that is, there are no pore fluids.

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Apollo 11 Drive-Tube Core Samples: An Initial Physical Analysis of Lunar Surface Sediment

Abstract. *Two drive-tube core samples were obtained at Tranquillity Base. Fines include much glass, are unweathered, medium gray, loose, nonstructured, very weakly coherent, and demonstrate both accumulation and mixing in a waterless vacuum environment. In contrast to chemical weathering characteristic on the earth, lunar alteration processes are primarily mechanical. We infer that environmental processes of the lunar surface may be expressed as follows:* R *(regolith)* = f(cl, p, r, t, b, a, . . .), *in which climate* (cl) *is constant and the time* (t)*-dependent processes of bombardment* (b) *and accumulation* (a) *assume significance unparalleled on the earth because of their effects on parent material* (p) *and relief* (r).

Two drive-tube core samples were collected successfully late during Apollo 11 exploration on the surface of the moon by Neil A. Armstrong and Edwin E. Aldrin, 20 July 1969. These cores thus provide the first samples of unconsolidated lunar surficial deposits and their subsurface characteristics.

During sampling, both drive tubes penetrated the first few inches easily, but required hammering to penetrate more deeply (Fig. 1) (*1*). The drive-tube samplers consist of an aluminum outer barrel, or tube, equipped with a disposable steel bit with inward taper at one end and a disposable aluminum handle at the other; the bit was replaced after use with a cap to protect and to retain the collected sample. An extractable aluminum split-tube assembly was housed inside the barrel to receive the sample as the tube was driven, and to permit later removal of the sample in undisturbed condition. This assembly consists of an anodized aluminum tube split lengthwise, surrounded by a Teflon sheath previously heat-shrunk into place to bind halves of the split-tube in position. A Teflon follower and steel spring are driven back inside the tube as the sample enters, and remain in place at the top of the sample to support it during trans-

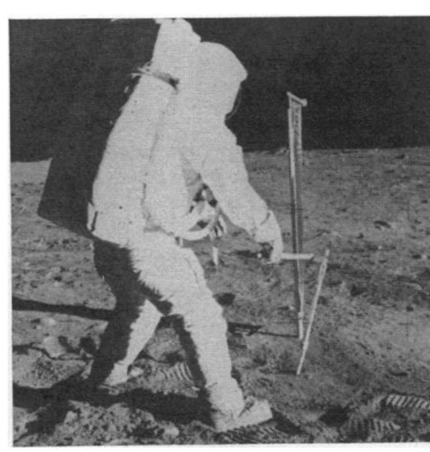

Fig. 1. Collection of Core Tube No. 1, approximately 3.5 m NNW of LEM, showing position relative to solar wind composition experiment in background. Note slant of tube and use of hammer required by Aldrin to drive it. [NASA photo AS11-40-5964 by Neil A. Armstrong]