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EFFECTS OF VERTICAL STRESS, TEMPERATURE AND DENSITY ON THE DIELECTRIC PROPERTIES OF LUNAR SAMPLES 72441,12, 15301,38 AND A TERRESTRIAL BASALT

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The dielectric properties of lunar soil samples 72441,12 and 15301,38 have been measured as a function of vertical stress to 2 bars, temperature to 200°C and density, in vacuum, over the frequency range $200-10^5$ Hz. It was found that the dielectric constant varies not only with density, but also with stress at constant sample density. The loss tangent was found to be insensitive, within experimental limits, to both stress and density variations over the ranges measured. A solid terrestrial basalt sample has been ground and the dielectric properties of the powder and a remaining portion of the solid sample have been measured in vacuum. The measured dielectric constants for the basalt soil at different densities are compared with calculated values using the solid sample data in conjunction with the Lichtenecker, Rayleigh and Krotikov-Troitskiy mixing formulas. Qualitative behavior of the dielectric properties of the lunar regolith with depth is discussed.

1. Introduction

Interest in the physical properties of granular media has become of major importance for the interpretation of physical models of the lunar regolith. Dielectric and d.c. conductivity data, in particular, have important applications for interpretation of earth-based radar observations [8], the Apollo 17 surface electrical properties experiment [20], the Apollo lunar sounder experiment [17], and the Standford-Apollo bistatic radar experiment [22]. Recognizing the need for electrical property measurements on soils, several laboratories have become involved in the measurement of lunar and lunar simulant soil samples [1, 5, 11, 15, 16, 21]. Until the present paper, however, no data as a function of increasing stress, temperature and density have been published for lunar soil samples. The main purpose of the present paper is to present the first electrical propert measurements on a lunar sample as a function of these thermodynamic variables.

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2. Experimental apparatus

The apparatus used to make the electrical property measurements in vacuum is shown in Fig. 1. The main body of the assembly (*a*) is fabricated from a 3-inch diameter stainless steel tube and was constructed so the upper portion is removable to facilitate sample placement and connection of electrical leads. A ceramic rod (*b*), used in application of vertical stress to the sample, is connected to the upper portion of the vacuum assembly. The three terminal molybdenum electrode system (*c*) and sample (*d*) are placed in a non-inductively wound furnace with a 250°C capability (*e*) which seats on a stainless steel thrust rod (*f*). Vertical movement of the thrust rod from outside the vacuum system is provided by means of a bellows (*g*) and guides (*h*). Weights are attached to the bottom of the thrust rod to balance the force due to atmosphere (approximately 2 bars) acting on the thrust rod and bellows when the system is evacuated. By removing weights, the sample assembly is then allowed to move toward the ceramic rod attached to the upper vacuum flange. Contact of the electrode assembly with the ceramic rod is determined by continuity between the guarded electrode and a thin molybdenum disk adhered to the end of the ceramic rod. The force acting on the sample is then given by the difference of the force due to atmosphere and the force of the weights with a small correction term to account for the force constant of the bellows. Using the apparatus in this manner, a minimum vertical stress of 0.04 bar (P_0) due to the weight of the upper electrode assembly and a maximum vertical stress of 2.0 bars could be applied to the sample. Higher stresses were obtained by placing the vacuum system in a jack assembly and applying additional force on the stainless steel thrust rod.

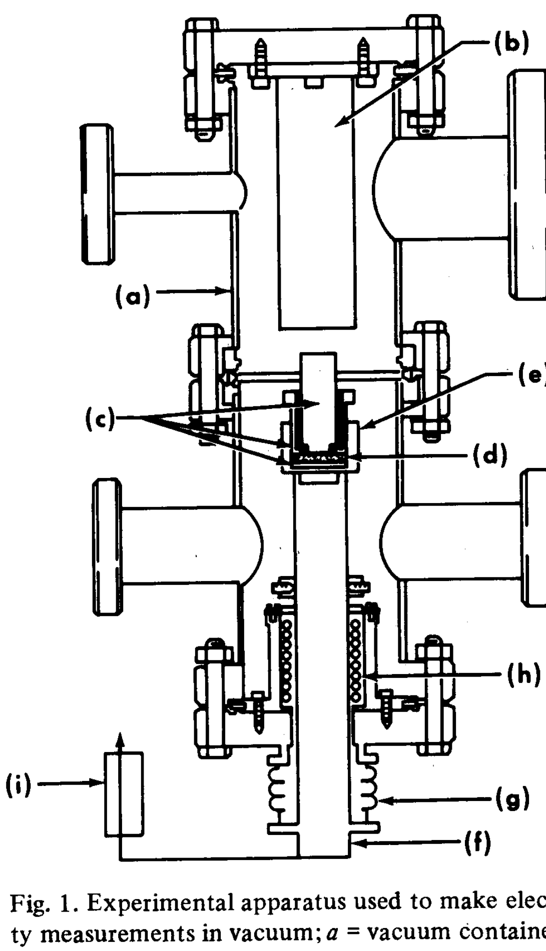

Fig. 1. Experimental apparatus used to make electrical property measurements in vacuum; *a* = vacuum container, *b* = ceramic rod, *c* = three terminal electrode assembly, *d* = sample, *e* = furnace, *f* = stainless steel thrust rod, *g* = bellows, *h* = alignment bearings, *i* = linear voltage differential transformer.

Displacements were measured using a linear voltage differential transformer (LVDT) (*i*) which has been calibrated to within 0.0002 inch. Electrical connections were made using General Radio 874 connectors and shielded cables. A Genereal Radio 1620-AF capacitance bridge was used to measure dielectric properties. Relative error of the dielectric measurements was 0.5% with an absolute accuracy of 2%. Dielectric measurements were made over a frequency range of 200 Hz to 15^5 Hz from 25 to 200°C.

Due to the high sensitivity of the LVDT, used to monitor thickness variations, effects of thermal expansion in the system precluded simultaneous vertical stress–temperature measurements. Consequently, all temperature measurements were made at P_0 and stress tests at room temperature.

3. Experimental technique and results

3.1. Lunar sample 72441,12

Lunar sample 72441,12 is an olive gray, soil sample with approximately 10% black cindery glass, 10% agglutinates, 10–15% white or light gray matrix breccia and 70% medium gray matrix breccia obtained on EVA2 of Apollo 17 from under a 2/3-m diameter rolled boulder. The sample was subjected to spacecraft atmosphere from 5 to 7 days, to terrestrial atmosphere 9–13 hours on the recovery ship and sealed in a static terrestrial atmosphere

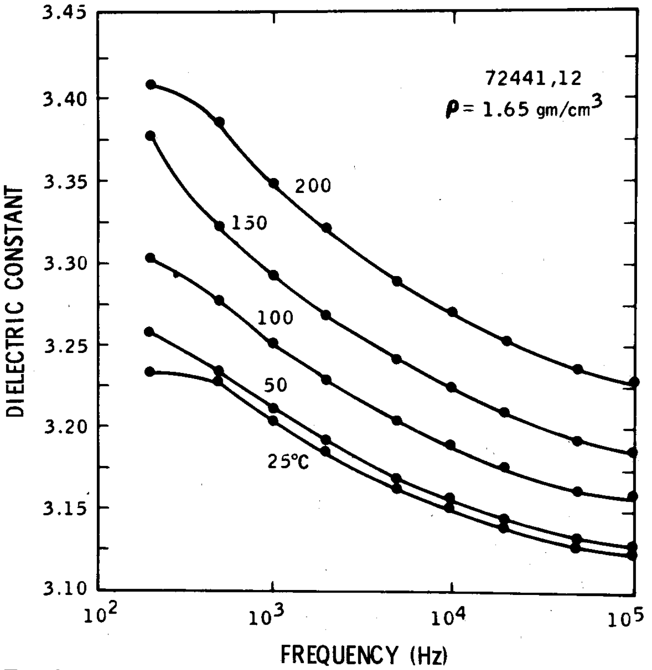

Fig. 2. Dielectric constant of lunar soil 72441,12 as a function of frequency for $\rho = 1.65$ g/cm^3 and constant temperature.

for about 1-1/2 days until introduction into the Lunar Receiving Laboratory nitrogen processing and storage atmosphere (Lunar Sample Information Catalog, Apollo 17, Johnson Space Center, Houston, Texas). To avoid further exposure to terrestrial atmosphere, the sample was transferred from its sealed bag to the experimental apparatus under a nitrogen atmosphere. The sample was placed in the sample holder and the upper electrode assembly

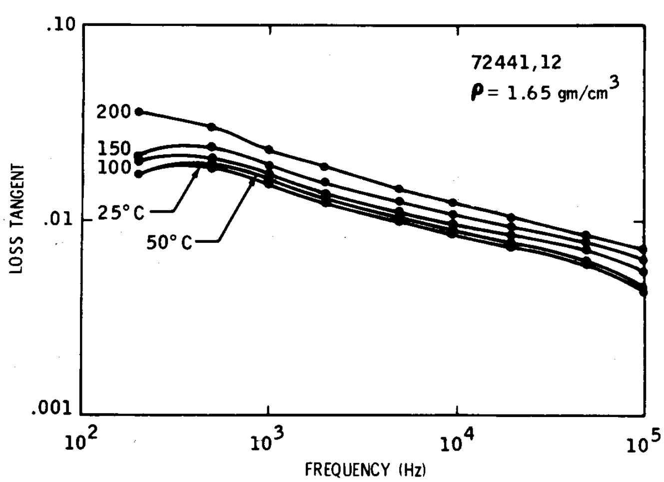

Fig. 3. Loss tangent of lunar soil 72441,12 as a function of frequency for $\rho = 1.65$ g/cm^3 and constant temperature.

placed on the sample. The thickness was then measured using a micrometer and an initial density of 1.65 g/cm^3 determined from mass to volume ratio. The initial stress on the sample due to the placement of the electrode assembly is approximately 0.04 bar (P_0). Immediately after transfer of the sample and final assembly of the system, the system was evacuated to 10^{-4} torr and dielectric data recorded at room temperature. Subsequent evacuation of the system to 2×10^{-7} torr had no noticeable effect on the dielectric data. When the sample was subjected to temperature, the pressure increased to about 2×10^{-5} torr at 100°C due to outgassing of the sample and sample holder with the majority of the outgassing presumably due to the history of the sample after it had been collected. In order to avoid the possibility of automatic shut down of the ion pump due to excessively high pressures, the ion pump was closed to the system and the roughing pump turned on. The sample was then taken to 200°C and left for 12 hours, the ion pump turned on, and the sample left for an additional 12 hours. After this procedure, the sample was then cooled to room temperature and the dielectric properties measured as a function of temperature from 25°C to 200°C. The dielectric constant and loss tangent for this test are shown in Fig. 2 and Fig. 3, respectively. Data recorded at room temperature before and after the vacuum-temperature treatment were nearly identical suggesting that water adsorbed by the sample was not the principal component in the observed outgassing.

A vertical stress of 2.0 bars was then applied to the sample which increased the density to 1.68 g/cm^3 and dielectric data recorded as the vertical stress was decreased to P_0. As shown in Fig. 4, the dielectric constant gradually decreases with stress release to about 0.34 bar, below which a much more rapid decrease is noted. This behavior is most certainly a result of better and more frequent grain contacts at the higher stress levels. As a part of a strength and compressibility test on just over 200 g of Apollo 12 soil (12,001,119), Carrier et al. [4] performed two rebound cycles to examine the elastic (recoverable) and plastic (irrecoverable) portions of one-dimensional settling induced by vertical stress. Their results showed that the elastic portion of the mechanical behavior of the soil was negligible compared to the

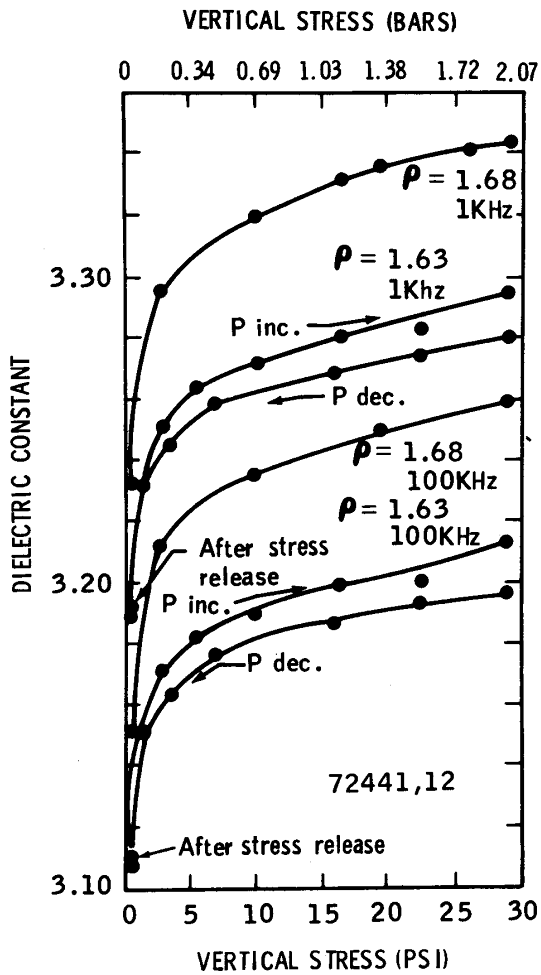

Fig. 4. Variation of dielectric constant of lunar soil 72441,12 as a function of vertical stress at 25°C.

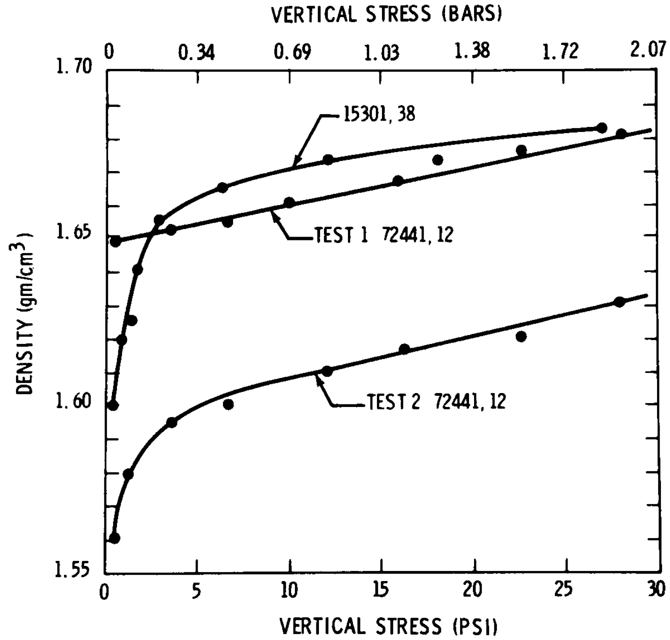

Fig. 5. Soil compression curves from stress tests for lunar sample 72441,12 and 15301,38.

plastic portion. Therefore, in the present experiment, the density is assumed to be essentially unchanged as pressure is decreased from 2.0 to 0.04 bar.

Dielectric data at densities intermediate to ρ_0 and ρ_{max} were not made due to the low compressibility of the thin soil sample which made experimental measurement of the raw dielectric data difficult. The compression data from the intermediate pressure recorded with the LVDT, however, can be used to establish a density–pressure relation that is useful for discussion of physical models of the lunar regolith. The compression curve for this test (Test 1) is shown in Fig. 5.

After completion of this test, the upper portion of the apparatus was removed under a nitrogen atmosphere and the thickness measured as a check on the thickness calculated with the LVDT data. This check showed excellent agreement between the two measurements. The sample was then stirred, smoothed and the vacuum system reassembled. The initial density in the second test was 1.56 g/cm^3. After evacuating to 2×10^{-7} torr for 24 hours, measurements were made to 200°C. Data for this test are shown in Fig. 6 and Fig. 7. After completion of the temperature test, the

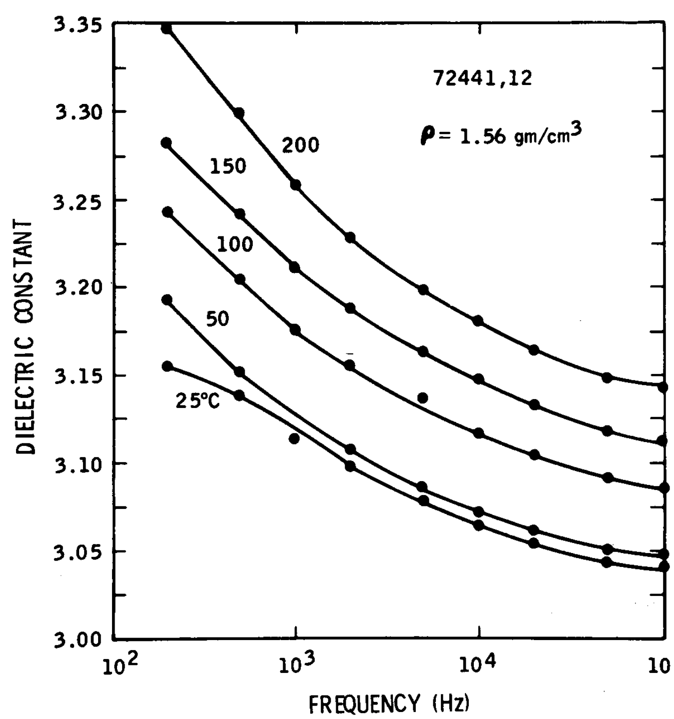

Fig. 6. Dielectric constant of lunar soil as a function of frequency for ρ = 1.56 g/cm^3 and constant temperature.

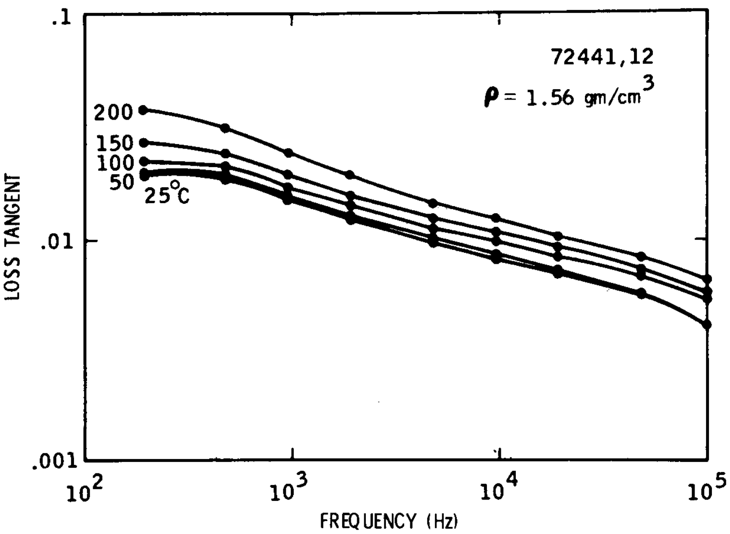

Fig. 7. Loss tangent of lunar soil 72441,12 as a function of frequency for ρ = 1.56 g/cm^3 and constant temperature.

sample was brought to room temperature and dielectric data remeasured. The data at room temperature before and after temperature cycling were in excellent agreement. A stress of 2.0 bars was then applied to the sample resulting in an increase in density to 1.63 g/cm^3. Dielectric data were then recorded as a function of decreasing stress at an essentially constant density of 1.63 g/cm^3. This data, illustrated in Fig. 4, shows the same qualitative behavior as the previous stress release test. To verify the effect of stress on the dielectric constant and to test for possible stress-induced dielectric hysteresis, data were then recorded as stress on the sample was increased from P_0 to 2.0 bars. These data, also illustrated in Fig. 4 (P_{inc}), show reasonable reproduction of the data recorded with decreasing stress (P_{dec}). After reaching maximum stress, the stress was brought back to P_0 and the dielectric properties remeasured. As shown in Fig. 4, no significant change in the data was observed after stress release.

To obtain higher densities the vacuum system was placed in a jack arrangement to compact the sample. The sample was subjected to pressure of approximately 3.4 bars with a resulting density of 1.80 g/cm^3, the stress released to eliminate stress effects, and a temperature test performed. These data are shown in Fig. 8 and Fig. 9. After completion of this temperature test, the sample was subjected to a vertical stress of approximately 6.9–8.6 bars which increased the density to 1.87 g/cm^3 and data recorded at room temperature. Finally, the system was opened and the

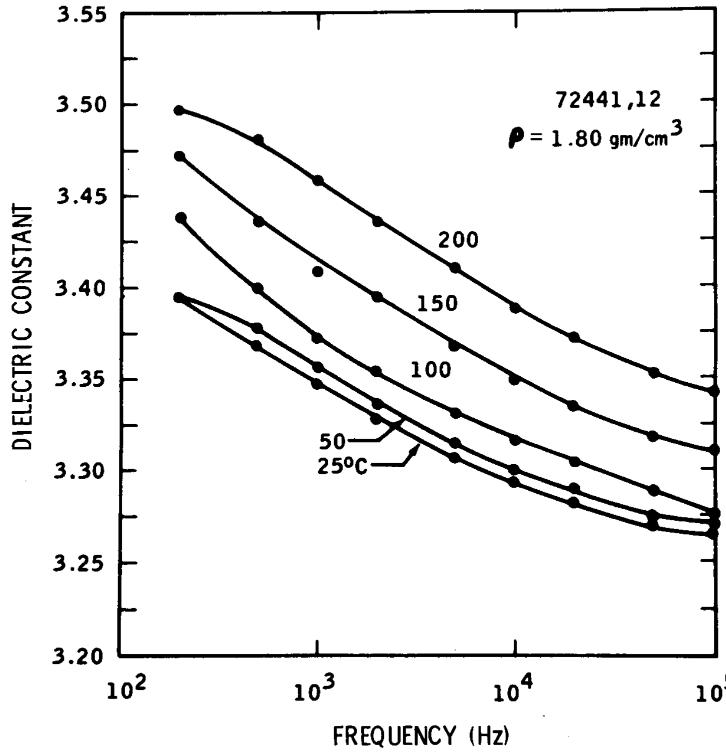

Fig. 8. Dielectric constant of lunar soil 72441,12 as a function of frequency for ρ = 1.80 g/cm^3 and a constant temperature.

thickness measured. The thickness was again in good agreement with that calculated using the LVDT. Data recorded for densities resulting from application of 2 bar and 6.9–8.6 bar maximum stress are shown in Fig. 10 and Fig. 11. These figures illustrate the dependence of the dielectric constant on density and the relative insensitivity of the loss tangent to density in the range measured.

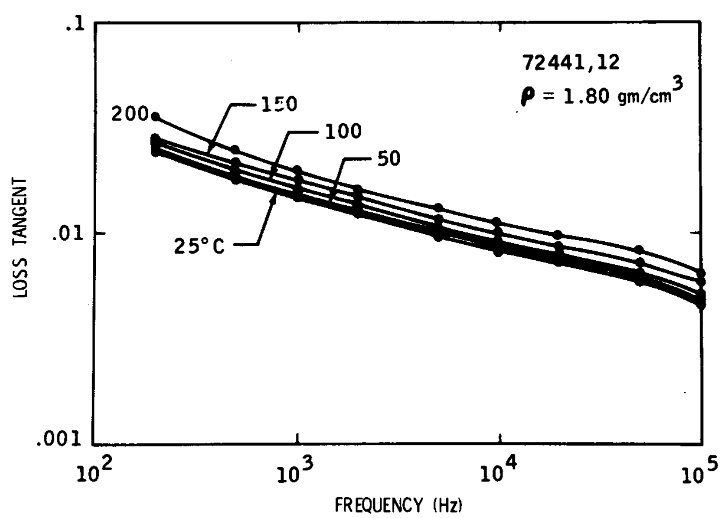

Fig. 9. Loss tangent of lunar soil 72441,12 as a function of frequency for ρ = 1.80 g/cm^3 at constant temperature.

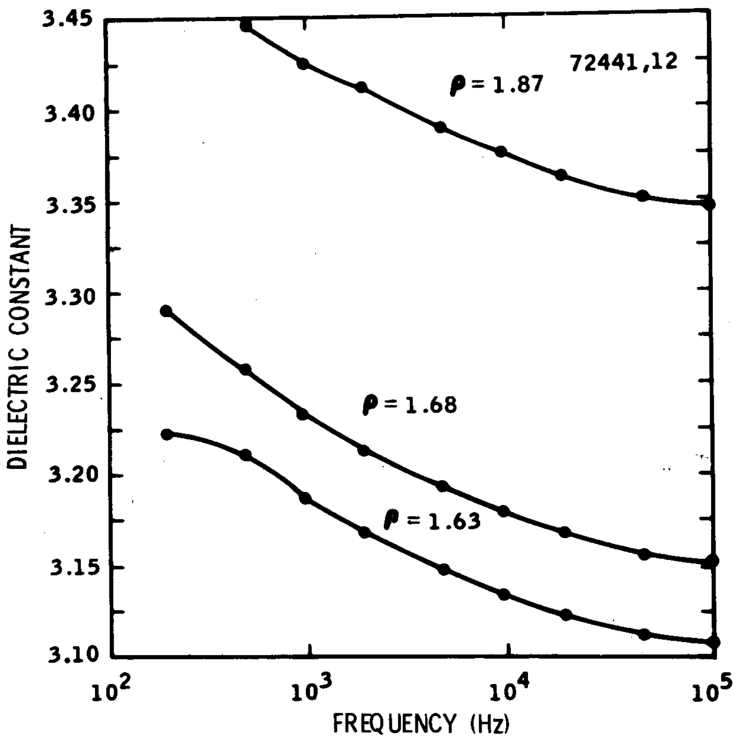

Fig. 10. Dielectric constant of lunar soil 72441,12 as a function of frequency for end points of each stress test. Data presented at $P = P_0$, $T = 25°C$.

Mathematical modeling of the dielectric data as performed by Olhoeft et al. [15] was not possible because no relaxation peaks were observed in the temperature and frequency range studied. In an attempt to obtain the data necessary for a mathematical description of the electrical properties, the sample was placed in a high vacuum-temperature system previous-

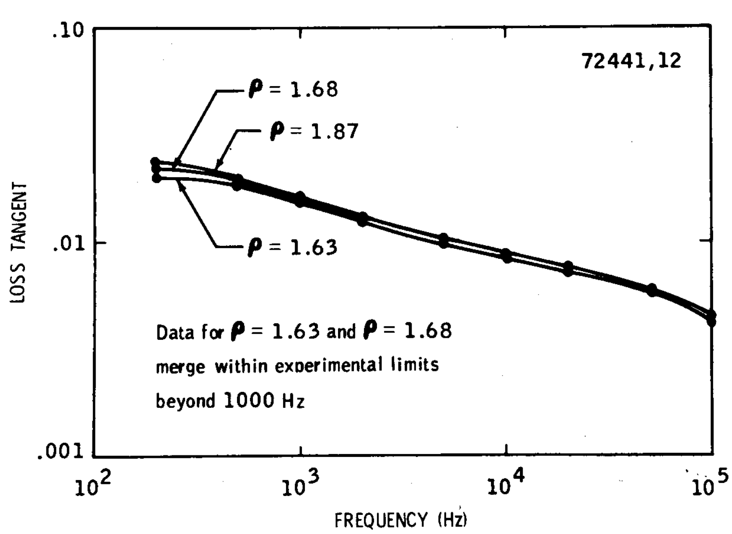

Fig. 11. Loss tangent of lunar soil 72441,12 as a function of frequency for end points of each stress test. Data presented at $P = P_0$, $T = 25°C$.

ly described by Olhoeft et al. [15]. Measurements were made in this system at 25, 125, 190, and 225°C. Unfortunately, because of what was interpreted as a rapid increase in the d.c. conductivity, no peaks were observed. The density of the sample in this test was 1.68 ± 0.07 g/cm^3. Dielectric data from the two systems were within estimated absolute accuracy but will not be presented in this paper as the supplementary data offers no additional information. In both systems, it was observed that, after initial pumpdown, temperature cycling had essentially no effect on the room temperature data even though significant outgassing occurred.

3.2. Lunar sample 15301,38

The electrical properties of lunar soil 15301,38 have been previously measured at a density of 1.47 ± 0.06 g/cm^3 and mathematical modeling of the electrical parameters performed [15]. The electrical properties of a portion of this sample have also been investigated in this experiment to provide additional information on the behavior of the dielectric properties with density and stress, with primary emphasis on effects of density changes. Because the sample had been exposed to air, the sample was subjected to vacuum-temperature treatment to a maximum temperature of 200°C until further treatment showed no change in the dielectric parameters. The initial density for this test was 1.60 g/cm^3 with density increasing to 1.68 g/cm^3 under vertical stress due to atmospheric force acting on the bellows (2 bars). The compression curve for this portion of the test is also shown in Fig. 5. To obtain higher densities, the sample was compacted using an external jack arrangement. The dielectric properties of lunar sample 15301,38 are given for selected frequencies at $T = 25°C$ and $P = P_0$ in Table 1. The dielectric constants measured at different densities agrees quite well with the earlier measurements performed at 1.46 g/cm^3 [15] in which the sample was not exposed to atmosphere. During the high-temperature tests performed on this sample [15], however, the loss tangent was irreversibly altered. Consequently, the loss tangent data reported in this paper for lunar soil 15301,38 are much higher than were measured before the high temperature tests.

At the highest measured density of 1.83 g/cm^3,

TABLE 1

Dielectric properties of lunar samples 72441,12, 15301,38 and terrestrial basalt sample at $T = 25°C$, $P = P_0$

Density	1 kHz		10 kHz		100 kHz	
	K'	tan δ	K'	tan δ	K'	tan δ
Lunar sample 72441,12						
1.56	3.11	0.015	3.06	0.008	3.04	0.004
1.63	3.19	0.015	3.13	0.009	3.11	0.004
1.65	3.20	0.015	3.15	0.009	3.13	0.004
1.68	3.23	0.015	3.18	0.009	3.15	0.005
1.80	3.35	0.015	3.30	0.009	3.27	0.006
1.87	3.42	0.016	3.38	0.009	3.35	0.005
Lunar sample 15301,38						
1.60	3.51	0.013	3.45	0.015	3.42	0.013
1.62	3.59	0.013	3.53	0.015	3.49	0.013
1.64	3.61	0.013	3.54	0.015	3.53	0.013
1.68	3.69	0.014	3.62	0.015	3.58	0.013
1.80	3.98	0.013	3.92	0.015	3.89	0.013
1.83	4.08	0.013	4.02	0.015	3.98	0.012
Terrestrial basalt						
1.49	2.64	0.036	2.55	0.015	2.52	0.005
1.56	2.68	0.037	2.58	0.015	2.56	0.005
1.58	2.69	0.037	2.60	0.015	2.57	0.005
1.61	2.71	0.038	2.61	0.015	2.58	0.005
1.75	2.88	0.038	2.78	0.015	2.75	0.006
1.81	3.08	0.038	2.98	0.016	2.94	0.006
1.96	3.33	0.042	3.22	0.016	3.18	0.006
2.13	3.84	0.047	3.69	0.019	3.64	0.007
3.0 (solid)	6.87	0.054	6.44	0.010	6.44	0.006

the pressure dependence of the dielectric constant was measured from approximately 2 bars to P_0 and is shown in Fig. 13.

3.3 Terrestrial basalt

A portion of a solid terrestrial basalt sample was ground to a powder and separated to a grain-size distribution similar to that of a sewed Apollo 12 soil [4]. Two faces on a remaining thin slab of the solid basalt sample were ground flat and, with the soil, provided the basis for measurements over a large density range. For both the solid and ground basalt samples, the preliminary vacuum-temperature treatment to reduce moisture effects consisted of maintaining the sample at 200°C for 48 hours under vacuum. Measurements of the soil were performed in a manner similar to that previously described.

Results of the measurements on the basalt soil at $P = P_0$ and $T = 25°C$, at selected frequencies are given in Table 1. The dielectric loss tangent for the lowest soil density attainable, $\rho = 1.49$ g/cm^3, the solid sample, and several intermediate soil densities are shown in Fig. 12, for a direct comparison of changes in the loss tangent with density. It is apparent, from this figure, that only small changes in the loss tangent are observed for relatively large changes in density. This is consistent with the observed relative insensitivity of the loss tangent with changes in density for lunar samples 72441,12 and 15301,38 in the respective density ranges measured.

The effect of stress release on the dielectric constant for a density of 1.61 g/cm^3 at 100 kHz is illustrated in Fig. 13. Comparing the basalt data in Fig. 13 with that for the lunar samples in Figs. 4 and 13, shows the effects of pressure release are qualita-

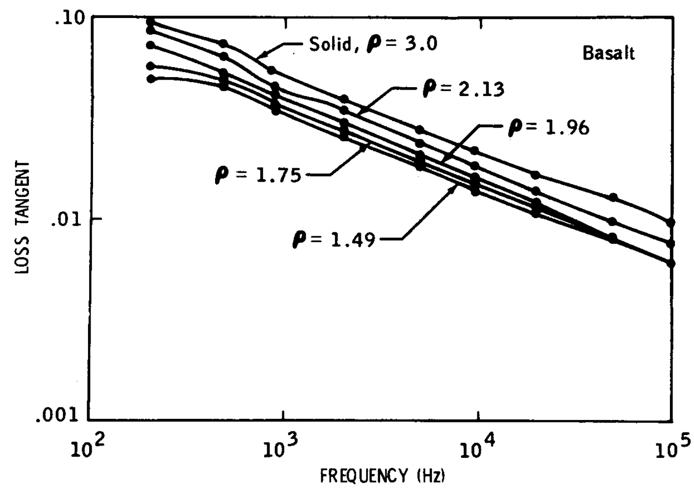

Fig. 12. Loss tangent of basalt as a function of frequency for ρ = 1.49, 1.75, 1.96, 2.13 and 3.0 g/cm^3 (solid).

tively similar, the effect being smaller for the terrestrial basalt.

4. Discussion of experimental results

The variation of dielectric constant with density for the terrestrial basalt powder sample is shown in

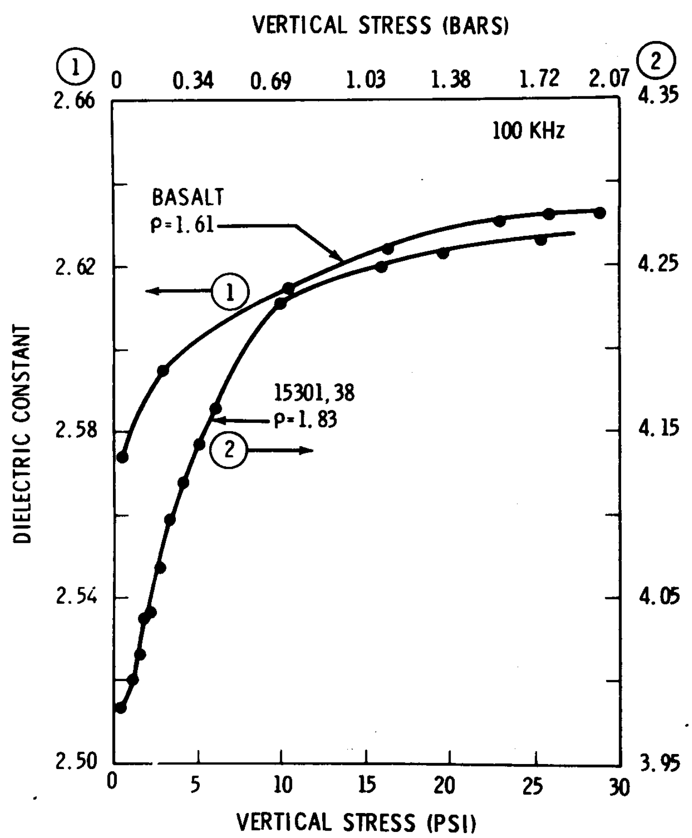

Fig. 13. Variation of dielectric constant of lunar soil 15301,38 and terrestrial basalt soil with vertical stress at 25°C.

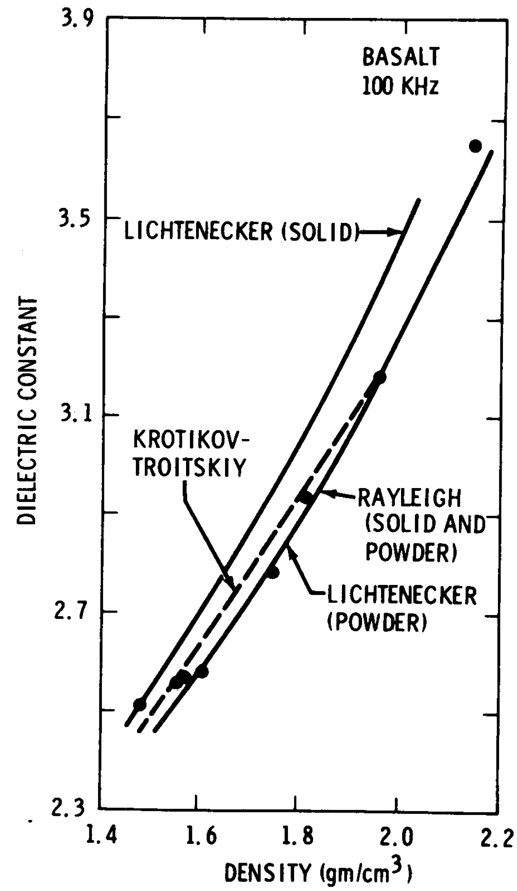

Fig. 14. Comparison of measured and calculated values of dielectric constants as a function of density for terrestrial basalt.

Fig. 14. Several expressions have been presented in the literature that may be used to determine dielectric constants as a function of density. Three prominent formulas are the Lichtenecker [23], Rayleigh [3], and Krotikov-Troitskiy [12, 13] formulas. These expressions are given below for reference:

Rayleigh:

$$\epsilon = \Pi\, \epsilon_{0i}^{1-P_i}$$

which reduces to $\epsilon = \epsilon_0^{\rho/\rho_0}$ for determining effects of density changes on a single material.

Rayleigh:

$$\frac{1}{\rho}\,\frac{\epsilon - 1}{\epsilon + 2} = \frac{1}{\rho}\,\frac{\epsilon_0 - 1}{\epsilon_0 + 2}$$

Krotikov-Troitskiy:

$$\epsilon = \epsilon_0 \left(1 - \frac{3P}{\dfrac{2\epsilon_0 + 1}{\epsilon_0 - 1} - P} \right)$$

where ϵ and ρ represent the permitivity and density of the soil, ϵ_0 and ρ_0 the corresponding values for the solid and $P = 1 - \rho/\rho_0$ is the soil porosity. Using the dielectric data for the solid basalt, the Rayleigh and Lichtenecker formulas were used to calculate dielectric constant as a function of density. As seen in Fig. 14, the Lichtenecker formula gives calculated values which are slightly higher than those experimentally determined, while the Rayleigh formula fits the data more precisely. This data indicates the Rayleigh formula is a reasonable approximation to the basalt soil sample if the data for the solid sample is known. This agrees with the high frequency results of Gold et al. [9] for measurements on several terrestrial samples..

For lunar samples, however, it is unreasonable to expect lunar fines and solids to be related by a mixing formula because of the physical and compositional differences between the returned soils and solids. It is more appropriate to measure the dielectric constant of the soil at high density and calculate the variation with decreasing density using a mixing formula. To examine the feasibility of using mixing formulas in this manner, the basalt soil data recorded at 1.93 g/cm^3 was used as the basis for calculating variation of dielectric constant with density. Both the Rayleigh and Lichtenecker formulas were nearly identical to the Rayleigh curve calculated using the solid basalt data. The Krotikov-Troitskiy formula was also used and the results of the three calculations are shown in Fig. 14. Within experimental limits, all formulas give a satisfactory approximation to the measured data.

The same mixing formulas were used to examine the calculated and measured values of dielectric constant for the two lunar soils as illustrated in Fig. 15. For sample 15301,38 all three formulas give a reasonable approximation to measured values but for sample 72441,12, all calculated curves are in significant disagreement with measured values. While it is possible that this disagreement reflects the lack of generality of mathematically describing the dielectric constant, K', versus density based on a single density measure [9], it is likely that a systematic experimental error is at fault. A comparison of the slope of the 72441,12 data with the terrestrial basalt and 15301,38, shows that the slope of the measured data for 72441,12 is considerably smaller. While it is not proper to linearly

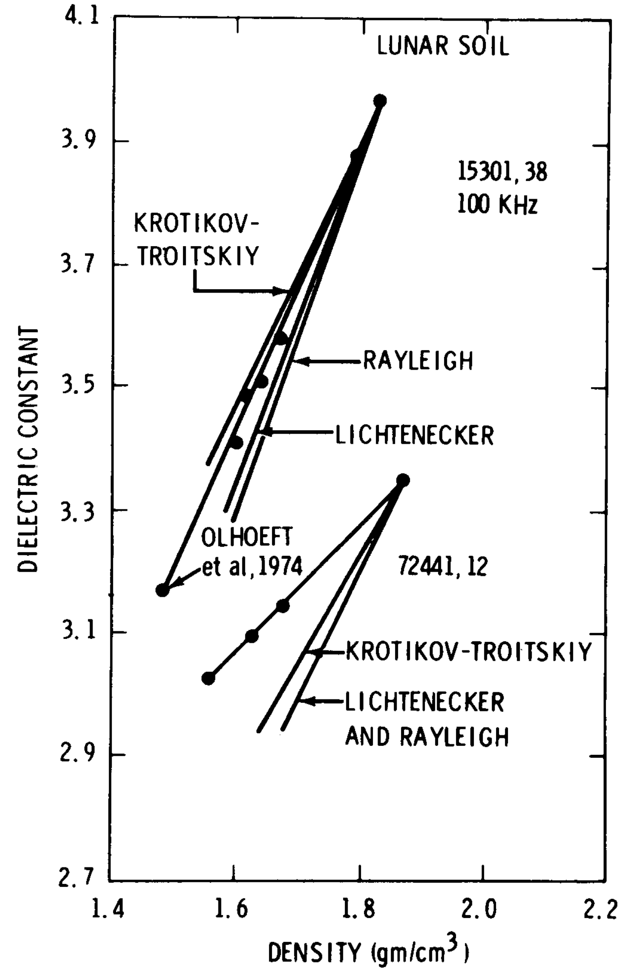

Fig. 15. Comparison of measured and calculated values of dielectric constants as a function of density for lunar samples 72441,12 and 15301,38.

extrapolate to zero density using the measured data, since the actual behavior is not linear, if the physical constraint

$$\lim_{\rho \to 0} K' = 1$$

is considered, a steeper slope is required than observed for this sample. At present, however, there is no known justification to modify the measured data to more adequately satisfy the curves calculated using the mathematical expressions. It is tentatively concluded that in spite of the discrepancies for the 72441,12 data any of the three mixing formulas may be used to calculate equally adequate representation of dielectric constant as a function of density.

From the data presented in this paper, it is certain that pressure influences the dielectric constant of soils. Examination of Figs. 4, 5 and 13 shows that the behavior is different for different soils and is related to soil density and is likely related to soil compressibility. To define the pressure dependence and the influence of soil compressibility, more data than are presented in this paper are required. Future efforts to investigate this phenomenon are planned.

The most important feature of the compression curves for sample 72441,12 shown in Fig. 5 is that the final densities of Tests 1 and 2 after stress application to 2 bars are so dissimilar. For a terrestrial sample, Carrier et al. [4] found the compression curves to merge at less than 0.69 bar for different initial densities. For lunar soil 12001,119, which is a very weakly coherent soil, they found the compression curves did not merge as stress was increased to 0.69 bar for different initial densities. What is surprising in the present data is that the compression curves do not merge even at pressure reaching 2 bars. While binding in the system caused by fine lunar powder working its way between the side of the guard electrode and the inner furnace wall is possible, only a small amount of fine powder was observed in this location after disassembling the apparatus. Therefore, the present data suggests either an important time dependent term associated with the compressibilities of lunar soils or that the lunar soil behavior under stress is significantly different than terrestrial soils. While it is possible that this phenomenon is related to the electric dipole moments of lunar soil grains [2], the compression behavior has not been thoroughly examined and is not well understood by soil mechanics investigators. A detailed study of the compressibility of lunar soils must be performed under controlled conditions to allow a better understanding of this phenomenon.

5. Qualitative inferences on the dielectric behavior and density of the lunar regolith

Several qualitative inferences regarding the behavior of the dielectric and density variation of the lunar regolith can be made from the present lunar sample data. Approximating the lower compression curve shown in Fig. 5 for lunar sample 72441,12 and the curve for sample 15301,38 by a straight line in the region 0.04–0.28 bar, the density variation with depth in the upper few meters of the lunar regolith due to self-compaction may be estimated. Using this approximation, as increase from 2 to 5% in density was calculated at 2 m. Such a small increase differs significantly from density–depth estimates from soil mechanics and drill core studies [14]. The fact that self-compaction accounts for only a small increase in density at 2 m supports the suggestion of Carrier et al. [4] that the lunar regolith may have experienced a greater confining stress at some time in the past than is presently applied to it by overburden pressure, i.e., the soil may be overconsolidated.

Using dielectric measurements on lunar powder simulant as a function of density and temperature, Alvarez [1] concluded the dielectric response of the uppermost layer of the regolith is controlled mainly by temperature variations and in the subjacent layer, by density. His conclusion, based on lunar powder simulant, is substantiated by the present measurements on actual lunar soil. In addition, the present results show that overburden pressure also influences the variation of dielectric properties with depth. Following Alvarez [1] by dividing the lunar regolith into two zones from 0 to 10 cm depth and 10 cm depth and below, the following qualitative behavior of the dielectric properties with depth may be established.

The upper 10 cm of the lunar regolith behaves in a complex manner, undergoing drastic temperature changes and a rapid density increase [4, 14]. Therefore, the dielectric constant within this region will be extremely variable depending on temperature, density and possibly stress whereas the loss tangent will be influenced almost entirely by temperature variations. Below 10 cm, where the effects of the lunar diurnal period are attenuated and the temperature remains essentially constant [10, 18], the principal factors influencing the dielectric constant are stress, density and mineralogy. Since the actual density and mineralogical distribution is vertically and laterally inhomogeneous, the dielectric properties will vary depending on the electrical properties of each sublayer. For each sublayer, however, overburden stress will increase, and consequently increase the values of the dielectric constant.

6. Conclusion

The dielectric properties of lunar sample 72441,12 have been measured as a function of vertical stress, temperature and density. The dielectric properties of lunar sample 15301,38 and a terrestrial solid and powdered basalt have been measured as a function of vertical stress and density. In all cases, the dielectric constant was found to increase with increasing stress and density. At constant density the dielectric constant increased rapidly with pressure from 0.04 to approximately 0.41 bar and then linearly, thereafter. The loss tangent was found to be relatively intensitive to density and pressure changes in the ranges measured.

It is tentatively concluded that the variation of dielectric constant with density may be approximated equally well with the Rayleigh, Lichtenecker or Krotikov-Troitskiy mixing formulas using dielectric data recorded on powders at high density.

Based on the present lunar soil measurements, the dielectric properties of the lunar regolith are expected to behave in the following qualitative manner. The upper 10 cm of the regolith behave in a complex manner, being influenced by marked temperature, pressure and density changes. In this region, the loss tangent appears to be sensitive primarily to temperature variation. Below 10 cm, the dielectric properties will vary depending on density, stress and the electrical response of each mineralogically different sublayer, but for a given sublayer, the effects of increasing stress and density will increase the value of the dielectric constant.

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