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ELECTRICAL PROPERTIES OF LUNAR SOIL DEPENDENCE ON FREQUENCY, TEMPERATURE AND MOISTURE

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We have examined the dielectric constant and loss tangent of a lunar soil sample in the frequency range from 100 Hz to 1 MHz. These results suggest that there is very little dispersion in the dielectric properties and that the loss tangent values are nearly a factor of 10 less than those measured by earlier studies. The d.c. conductivity is very low, around 10^{-14} to 10^{-15} Ω^{-1}/m at room temperature and is strongly temperature-dependent with an activation energy in the range of 0.4 – 0.9 eV. The introduction of atmospheric air has a profound influence on the electrical properties. The dielectric constant and loss tangent increase at frequencies below 10 kHz due to the presence of the moisture. The loss tangent increases by nearly a factor of 50 at the lower frequencies and the d.c. conductivity increases by 4 orders of magnitude. In order to make measurements on samples that represent lunar conditions it is essential to take great precautions to remove all residual moisture.

1. Introduction

With the return of samples from the moon it has become possible to measure directly many of those properties which previously were inferred only from remote sensing techniques. Among these properties are the electrical properties of the materials at the lunar surface. A review of these results was published by Ward [15] and by Strangway [13], showing typical penetration depths that might be expected on the lunar surface by electromagnetic energy at various frequencies. The essential data that contributed to the earlier reviews were the following: a) analysis of infrared and microwave thermal emission and radar reflections at frequencies of 10^{10} Hz and higher [16], b) study of energy reflected from the moon by the communication systems of the Lunar Orbiter at 136 MHz [14] and c) the study of dried rocks in earth laboratories [12]. Since that time there has been a considerable amount of work done on the electrical properties of lunar samples and additional results are reported in the present paper. Katsube and Collett [10], Chung et al. [2 – 4] and Chung et al. (in press) have reported on the dielectric constant and loss tangent of lunar soil and rock samples in the frequency range from 100 Hz to about 10 MHz. Some of these results have been discussed by Rossiter et al. [11]. In addition, Campbell and Ulrich [1] and Gold et al. [6 – 8] have shown that at 450 MHz, the attenuation distance in lunar samples is in the range from 10 to 70 wavelengths. Using data from reflections from the communications systems of the Apollo spacecraft, Howard and Tyler [9] have shown that the dielectric constant of the lunar surface is about 3.0 at 0.13 m. At a wavelength of 1.16 m the irregular character of the reflections suggests subsurface structure. These results are summarized in fig. 1.

We wish to report in this paper on a new set of mea-

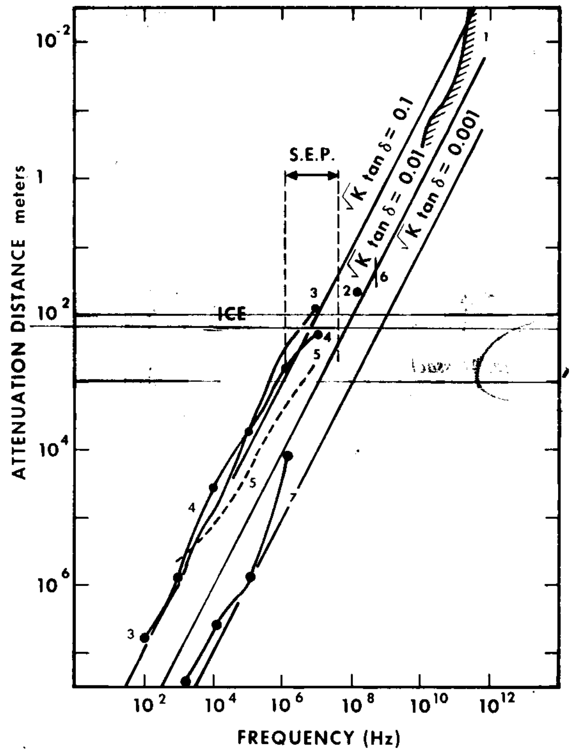


Fig. 1. Attenuation distance versus frequency for various values of $\sqrt{K}\tan\delta$. 1) [16]; 2) [14]; 3) [10] – lunar igneous sample; 4) [10] – lunar breccia sample; 5) [10] – soil; 6) [7] – lunar fines; 7) Present paper – lunar soil sample.

surements on a soil sample (14 63,131) from the Apollo 14 site. This sample was collected on EVA I and returned to earth in Apollo Lunar Sample Return Container (ALSRC) No. 1007 which was vacuum-sealed on the moon. On return to the Lunar Receiving Laboratory (LRL) it was found that it had not sealed properly, but the sample was processed in the LRL in dry nitrogen and subsequently triple-sealed in teflon bags. It was then stored in dry nitrogen and transferred into our measuring system in dry nitrogen without exposing the sample to air.

The measurements were made using a three-electrode system with a vacuum system capable of pumping the sample space down to 10^{-7} torr or less. A furnace capable of heating the sample to several hundred °C was also available. The dielectric measurements in the range from 100 Hz to 100 kHz were made with a General Radio 1615 bridge and the measurements at 1 MHz were made with a General Radio 1682 bridge. Measurements of the d.c. resistivity were made using a Hewlett – Packard 4329 high-resistance meter.

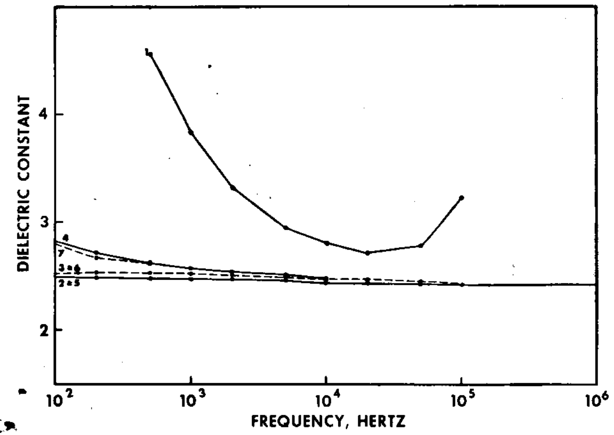
2. Experimental results

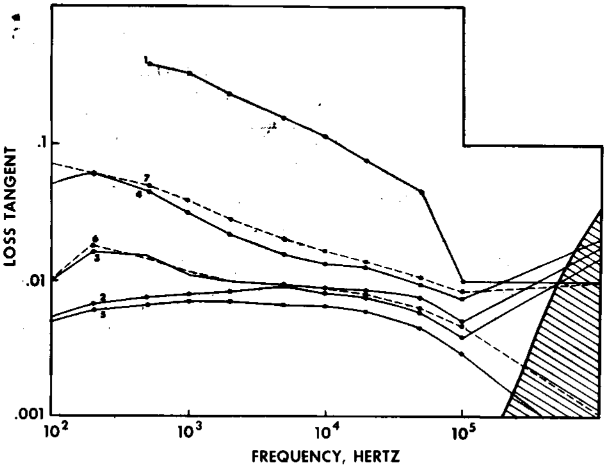
Before examining the results from the lunar samples we show a comparable set of results from an earth sample. In this case we have examined a sample of granite from Barrie, Vermont. We examined both a powdered sample and a piece of the solid granite. The powder was lightly packed but no estimate of the density was made. The measurements of dielectric constant and loss tangent for the powder are shown in fig. 2a and b.

Initial measurements at room temperature and before evacuating the sample show a strong dispersion at low frequency. This behavior is characteristic of samples containing moisture [12]. After the sample has been evacuated and heated to 250°C the dispersive effect has been completely eliminated so that the dielectric constant, at room temperature, is essentially frequency-independent, with a value of about 2.5. The loss tangent is slightly frequency-dependent, and has a value of about 0.008 at room temperature.

The d.c. electrical conductivity of this sample was also measured as a function of temperature (fig. 2c). At room temperature the conductivity approaches 10^{-15} Ω^{-1}/m. At 200°C, the conductivity has risen to about 10^{-11} Ω^{-1}/m showing a very strong temperature dependence.

A piece of solid granite was also examined in the same way and the results are shown in figs. 3a and 3b. Because of packing, the dielectric constant is higher with a value of about 6.0. At room temperature and pressure, a strong low-frequency dispersion is also found. However, evacuation of the sample and heating of the sample to 250°C, through 2 cycles, almost entirely removed the low-frequency dispersion in the dielectric constant and reduced the loss tangent values to about 0.02. This value is somewhat higher than that of the powder but it is still low and fairly insensitive to frequency, with a similar shape to that of the powder. Erratic values found during the first heating probably represent an intermediate stage when free water was removed but some adsorbed water was still present. It appears that the low-frequency dispersion which has been reported on by many investigators (see ref. [12] for example) is largely the result of residual moisture.





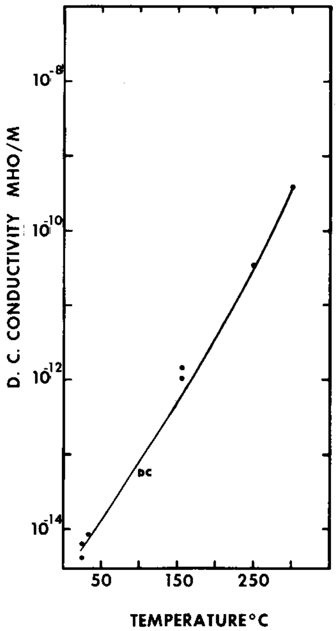


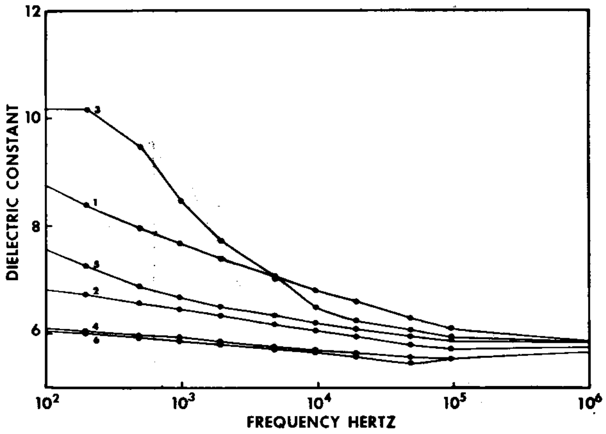
Fig. 2. a) Dielectric constant versus frequency for a sample of powdered granite from Barrie, Vermont. 1) 27°C, atmosphere; 2) 27°C, 10^{-6} torr; 3) 150°C, 10^{-5} torr; 4) 200°C, 10^{-5} torr; 5) 27°C, 2 X 10^{-7} torr; 6) 200°C, 1.5 X 10^{-7} torr; 7) 250°C, 8 X 10^{-7} torr. b) Loss tangent versus frequency (shaded area represents limit of commercial bridges). 1) 27°C, atmosphere; 2) 27°C, 10^{-6} torr; 3) 150°C, 10^{-5} torr; 4) 200°C, 10^{-5} torr; 5) 27°C, 2 X 10^{-7} torr; 6) 200°C, 1.5 X 10^{-7} torr; 7) 250°C, 8 X 10^{-7} torr. c) d.c. conductivity versus temperature after evacuating to 10^{-7} torr.

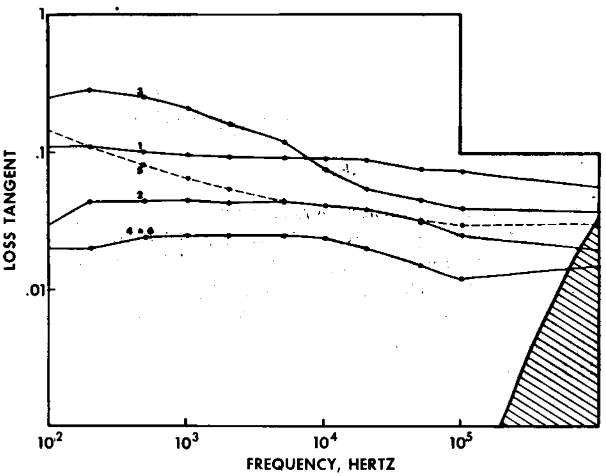
Evacuation to 10^{-7} torr and one or more thermal cycles to 200 or 250°C seems to completely remove these effects. The remaining effect in both dielectric constant and loss tangent is nearly independent of frequency at room temperature.

At temperatures of about 200°C after thermal cycling a small dispersion effect is noticeable at low frequencies in both the powder and the solid. The effect is quite small in the powder and fairly small in the solid but it is clearly present. We believe that this is the result of a Maxwell – Wagner effect associated with variation in properties from place to place in the sample. The fact that it is different for solids and powders suggests that it is associated with differences in grain contacts [12].

The d.c. conductivity of the solid has a behavior very much like that of the powder, except that the conductivity is higher by a factor of about 10, undoubtedly due to better grain contacts. The effect is slightly more strongly dependent on temperature as seen in fig. 3c and table 1. The value of d.c. conductivity is extremely low and comparable to that of the best insulators available.

The results from the lunar sample we have examined are shown in fig. 4. Measurements were made after the sample had been handled in dry nitrogen and then pumped down to 10^{-6} torr. Very little difference was found when this was done and the dielectric constant of 2.26 is nearly frequency-independent at room temperature. The loss tangent values are very low and show a decrease with frequency from 100 Hz up to the highest frequencies used. The actual values are very low and approach 0.001 at 100 kHz, at room temperature. These values are nearly a factor of 10 less than those





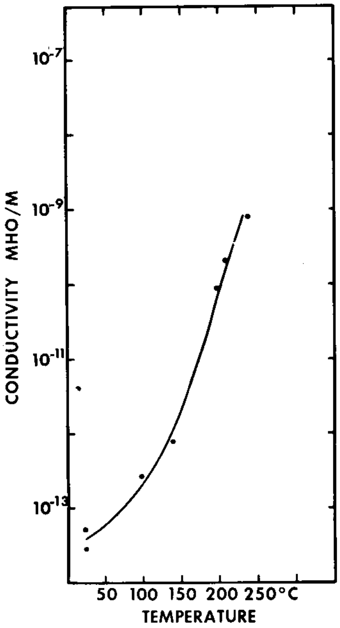


Fig. 3. a) Dielectric constant versus frequency for a sample of solid granite from Barrie, Vermont. 1) 27°C, atmosphere; 2) 27°C, 10^{-6} torr; 3) 200°C, 4 × 10^{-6} torr; 4) 27°C, 9 × 10^{-8} torr; 5) 200°C, 10^{-7} torr; 6) 27°C, 1.2 × 10^{-7} torr. b) Loss tangent versus frequency. 1) 27°C, atmosphere; 2) 27°C, 10^{-6} torr; 3) 200°C, 4 × 10^{-6} torr; 4) 27°C, 9 × 10^{-8} torr; 5) 200°C, 10^{-7} torr; 6) 27°C, 1.2 × 10^{-7} torr. c) d.c. conductivity versus temperature on final heating after evacuating to 10^{-6} torr.

measured previously on other lunar samples suggesting that the dryness is an important factor in controlling the losses. There is a clear temperature dependence of both the dielectric constant and the loss tangent, but again there is not a strong frequency dependence.

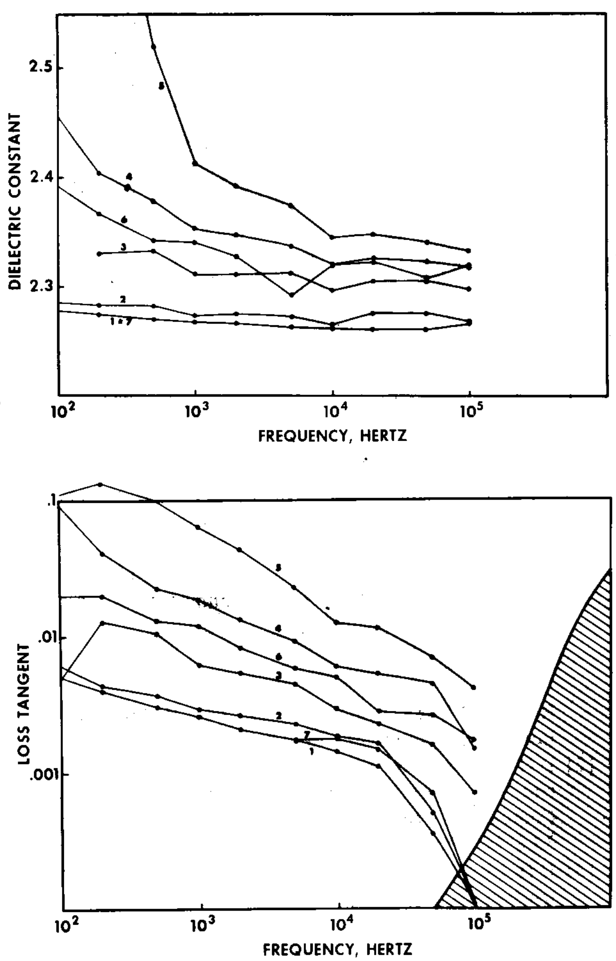
The d.c. conductivity values are shown in fig. 4c. The values are quite comparable to those for the powdered granite and it appears that this type of behavior may be characteristic of powdered, rock material. Interestingly enough, the activation energies for the terrestrial rock and powder and the lunar soil are all about the same (table 1). Values of about 0.5 to 1 eV seem to be typical of dry rocks and suggest that this phenomenon is not an intrinsic property of material but related to imperfections, impurities and perhaps surface properties.

Table 1
Activation energies of d.c. conductivity (eV).

Barrie granite, powder	0.50 – 0.84
Barrie granite, solid	0.57 – 0.70
Lunar sample 14 163, 131	0.43 – 0.91

3. Effects of moisture

We have already seen in the terrestrial samples that pumping out the atmospheric air and thermal vacuum cycling clearly removes the bulk of the dispersion effects at low frequencies. To test the influence of moisture on the lunar sample we conducted a specific set



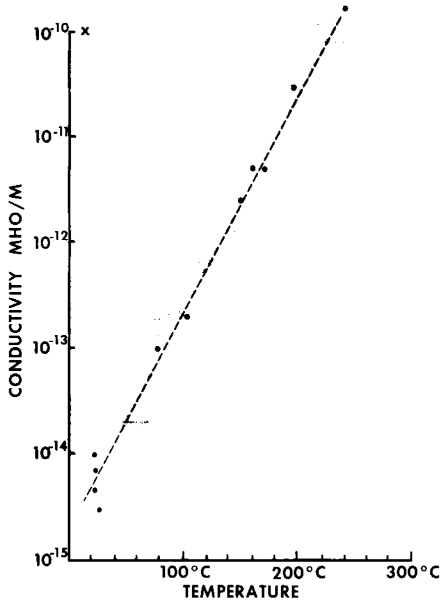


Fig. 4. a) Dielectric constant versus frequency for lunar sample 14 163,131. 1) 27°C, 3 × 10^{-7} torr; 2) 100°C, 3 × 10^{-7} torr; 3) 160°C, 4 × 10^{-7} torr; 4) 200°C, 10^{-6} torr; 5) 240°C, 10^{-6} torr; 6) 150°C, 3 × 10^{-7} torr; 7) 27°C, 2 × 10^{-7} torr. b) Loss tangent versus frequency (shaded represents limits of instrumentation). 1) 27°C, 3 × 10^{-7} torr; 2) 100°C, 3 × 10^{-7} torr; 3) 160°C, 4 × 10^{-7} torr; 4) 200°C, 10^{-6} torr; 5) 240°C, 10^{-6} torr; 6) 150°C, 3 × 10^{-7} torr; 7) 27°C, 2 × 10^{-7} torr. c) d.c. conductivity versus temperature after evacuating to 10^{-7} torr (X = value with air present).

of experiments. First the sample was exposed to dry nitrogen and there was essentially no influence on the dielectric constant and loss tangent. The sample was then reevacuated, the measurements remade and the sample then exposed to air. The results of these measurements are shown in fig. 5. It can be seen that the dielectric constant at frequencies less than 10 kHz is strongly affected and shows a strong, characteristic dispersion. Similarly the loss tangent below 10 kHz increases drastically, by almost a factor of about 20.

The sample was then reevacuated and the dielectric constant and loss tangent returned to nearly their original values. It is thus clear that even a small amount of humidity in the sample has a profound influence on the observations. The loss tangent in particular, is strongly affected. At the same time, the d.c. conductivity value increased by four orders of magnitude suggesting that moisture has the effect of providing an electrical path through the material, perhaps by providing a surface adsorbed layer on the grains. After measurements were done at room temperature the sample was subsequently evacuated to 10^{-6} torr and the measurements found to be almost the same as the original measurements. Subsequent heating only reduced these values slightly, suggesting that the moisture effects due to exposure to air for about one hour were readily removable.

4. Conclusions

The dielectric constant and loss tangent of lunar

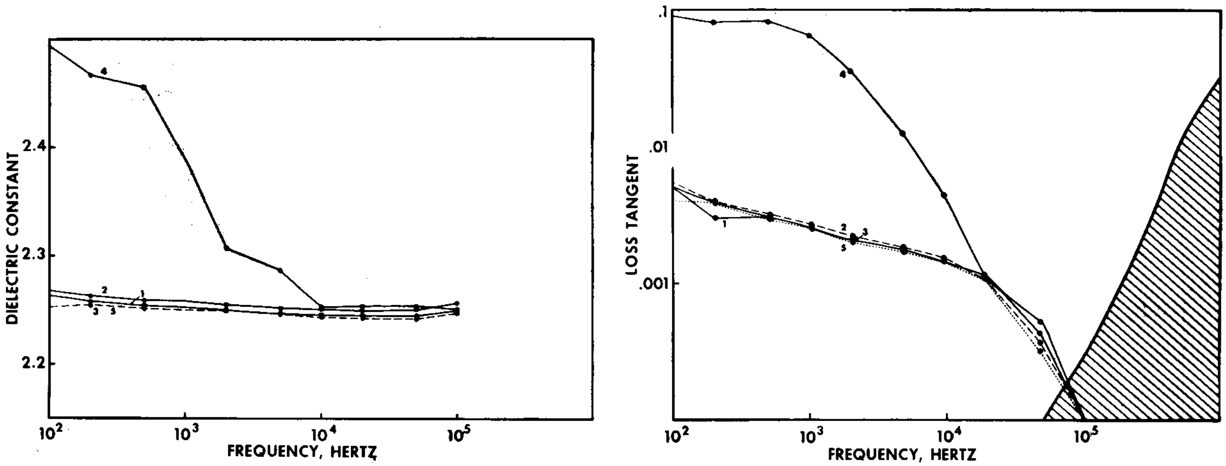


Fig. 5. a) Dielectric constant as a function of frequency for lunar sample 14 163,131 showing the influence of moisture at room temperature. 1) 27°C, 10^{-5} torr after several thermal cycles; 2) 27°C, 5 × 10^{-7} torr after exposure to 1 atm of dry nitrogen; 3) 27°C after heating to 200°C; 4) 27°C, atmospheric pressure, air; 5) 27°C, after pumpdown back to 10^{-6} torr. b) Loss tangent as a function of frequency for lunar sample 14 163,131. 1) 27°C, 10^{-5} torr after several thermal cycles; 2) 27°C, 5 × 10^{-7} torr after exposure to 1 atm of dry nitrogen; 3) 27°C after heating to 200°C; 4) 27°C, atmospheric pressure, air; 5) 27°C, after pumpdown back to 10^{-6} torr.

soil samples in the range from 100 Hz to 1 mHz are not strongly dependent on frequency provided considerable care is taken to avoid exposure of the sample to atmospheric air containing moisture. The loss tangent turns out to have a surprisingly low value, lower by nearly a factor of 10 than any previously reported values. The data from this lunar sample are included in fig. 1, which show that at 1 mHz, the penetration depth in lunar soil is expected to be around 10 km. This implies that the surface layers of the moon are likely to be extremely transparent to radio waves. At the same time, the d.c. conductivity is found to be about 10^{-14} to 10^{-15} Ω^{-1}/m at room temperature and to be strongly dependent on temperature.

The influence of atmospheric moisture is to introduce a strong dispersion in the dielectric constant and loss tangent below about 10 kHz and to increase the d.c. conductivity by four orders of magnitude. Clearly great care needs to be taken in making measurements on returned lunar samples to ensure that moisture does not bias the results.

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