Measurement of the Dielectric Properties of Granular Materials

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***Abstract*—We have developed an AC impedance measurement technique to study the dielectric properties of granular materials. The method involves placing a fixed volume of granular materials between two parallel metal plates, thus forming a dielectric filled capacitor. The response of the sample to a frequency dependent applied voltage is measured, from which the effective resistance and capacitance of the granular material is obtained. The dielectric constant of the granular material is obtained from the effective capacitance. Results are presented for a granular sample consisting of the Martian soil simulant known as JSC Mars-1 under low humidity conditions in a low vacuum environment.**

I. Introduction

Compared to bulk materials, it is much more difficult to reliably measure the dielectric properties of granular materials. Granular materials consist of an unknowable number of particles in various orientations and having various shapes and sizes. This makes it very challenging to actually measure the physical properties of granular materials. And it is impossible to construct a precise theoretical model when physical properties like resistivity depend upon a knowledge of the interparticle contacts, which is not something that can be known with a high degree of certainty.

NASA's Viking and Mars Pathfinder missions each employed onboard instruments to determine the composition of the Martian soil at their respective landing sites. Those findings led to the development of a Martian soil simulant (JSC Mars-1) at NASA Johnson Space Center. However, in spite of the compositional studies conducted during those previous missions, no direct measurements were ever made of the dielectric properties of the Martian soil. In the present study, a three-electrode system was used to measure the frequency response to an applied sinusoidal voltage of finely ground Martian soil simulant that was placed in a dry, low-vacuum environment.

II. THEORETICAL MODEL

Huggins and Sharbaugh[1] introduced a simple model for powdered organic semiconductors in which individual particles of resistance R_s and capacitance C_s are separated by series contacts having resistance R_c and capacitance C_c. The equivalent circuit, shown in Fig. 1 (d), consists of an effective resistance R_p in parallel with an effective capacitance C_p. The granular material was lightly packed between the parallel plates of a capacitor and AC impedance measurements were made.

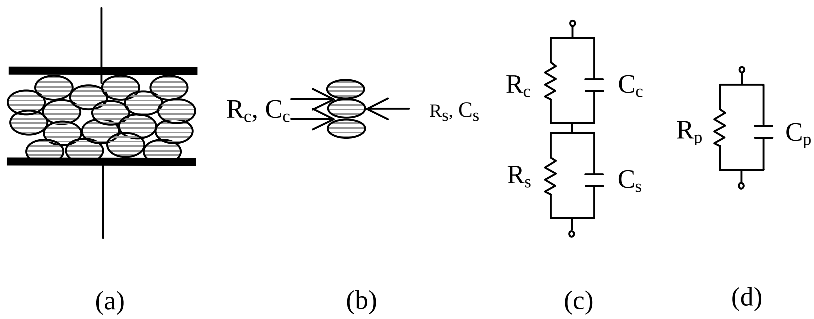

Fig. 1. (a) Particles are shown interspersed between two parallel metal plates. (b) Resistance R_s and capacitance C_s of individual particles, and contact resistance R_c and contact capacitance C_c between particles. (c) Circuit model for particles and interparticle contacts. (d) Equivalent circuit.

Data obtained from NASA's Viking and Mars Pathfinder missions resulted in the development of a Martian soil simulant using minerals found on earth [2]. The breakdowns by percentage weight of the actual Martian soil as well as the Martian soil simulant, known as JSC Mars-1, are shown below in Table 1.

We have developed an AC impedance measurement technique in an effort to study the dielectric properties of the JSC Mars-1 soil simulant. This method consisted of placing the simulant particles between two metal parallel plates to form a capacitor similar to that shown in Fig. 1(a). The Martian soil simulant particles serve as a dielectric medium for a capacitor that has an effective capacitance C_p and effective resistance R_p due to some of the minerals in the simulant being semiconductive, such as iron oxide. The capacitor containing the soil simulant was placed in series with a fixed capacitor C_A = 1 nF whose other terminal was grounded as shown in Fig. 2. A sinusoidal voltage of amplitude V_a and frequency f was applied to one of the electrodes of the capacitor that contained the Martian soil simulant. The output voltage V_{out} was measured at the point between the two capacitors. Use of a guarded lower electrode, which is not shown in Fig. 1(a), significantly reduced edge effects. The guard surrounds the sensing electrode of C_p where V_{out} is measured. A non-inverting op amp circuit keeps the voltage at the guard electrode at the same level as the sensing electrode.

TABLE 1: COMPOSITIONS OF MARTIAN SOIL AND TWO VERSIONS OF SIMULANT

Oxide Type	Viking 1 Wt %	Viking 2 Wt %	Pathfinder Wt %	JSC Mars-1 (Sample A) Wt %	JSC Mars-1 (Sample B) Wt %
SiO_2	43	43	44	34.5	43.5
Fe_2O_3	18.5	17.8	16.5	12.4	15.6
Al_2O_3	7.3	7	7.5	18.5	23.3
SO_3	6.6	8.1	4.9	-	-
CaO	5.9	5.7	5.6	4.9	6.2
MgO	6	6	7	2.7	3.4

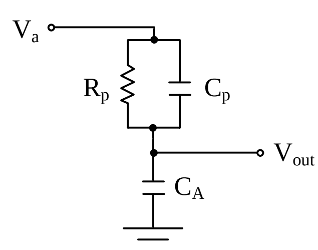

Fig. 2. Simplified schematic of the electronic circuit used in this study to measure the dielectric properties of a known volume of granular material. The volume of granular material is assumed to have an effective capacitance C_p and an effective resistance R_p. The applied input voltage V_a is a purely sinusoidal signal of frequency f. The output voltage V_{out} is measured as a function of frequency across a fixed capacitor C_A = 1 nF.

Using standard circuit analysis, the circuit shown in Fig. 2 is found to have a frequency dependent voltage gain that is described by the equation

$$\left|\frac{V_{out}}{V_a}\right| = G\frac{\sqrt{\left[\omega_p^{\,2}+\left(1+\frac{C_A}{C_p}\right)\omega^2\right]^2+\left[-\frac{C_A}{C_p}\omega_p\,\omega\right]^2}}{\omega_p^{\,2}+\left(1+\frac{C_A}{C_p}\right)^2\omega^2} \tag{1}$$

where $\omega_p \equiv 1/R_p C_p$ and $\omega = 2\pi f$. In the actual circuit used in this study, a non-inverting amplifier with a gain of G = 39.5 was used to amplify the output signal shown in Fig. 2. The difference in phase between the input signal $V_a(t)$ and the output signal $V_{out}(t)$ may also be calculated, but the result is not presented here.

III. RESULTS AND DISCUSSION

Before conducting the experiment, the JSC Mars-1 soil simulant was baked in an oven at an elevated temperature to eliminate the water content from the soil. The soil was taken from the oven and immediately poured into the capacitor to fill up the space between the plates of the capacitor C_p. The capacitor was shaken slightly while the granular soil simulant was being poured, resulting in a lightly packed volume of material. The measurements were performed at room temperature in a vacuum chamber that had first been purged several times with dry air, and then pumped down to a pressure of 0.3 Torr. A digital oscilloscope was used to measure the peak-to-peak voltages of the input signal V_a (2 V amplitude at frequency f) and the output signal V_{out}. The data was found to be reproducible, and is shown (x symbols) in Fig. 3 along with the results of a theoretical calculation based on (1).

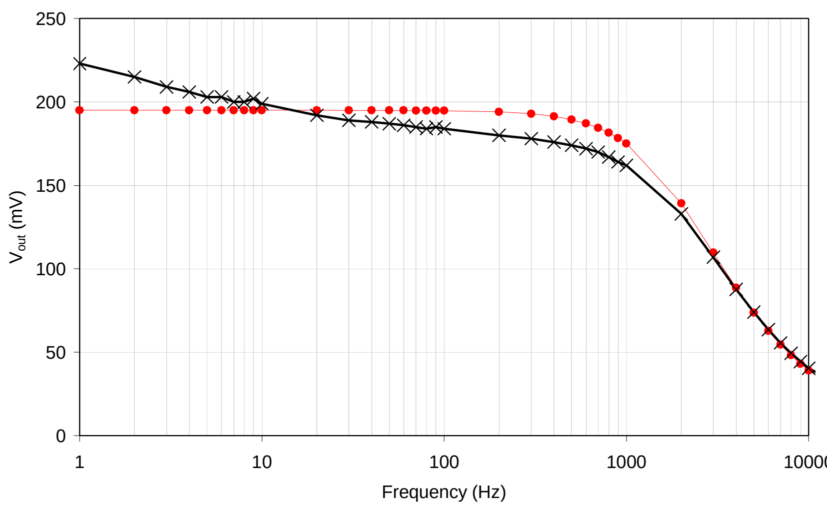

Fig. 3. The frequency responses of the measured output voltage V_{out} (represented by x symbols) and the theoretical values (represented by dots) of V_{out} based on (1) using three fitting parameters.

As Fig. 3 illustrates, there is some agreement between the measured data and the theory used to model the granular JSC Mars-1 soil simulant. Parameter values of $\omega_p = 2\text{x}10^8$ rad/s, C_p = 0.01 pF, and G = 0.1 were used to construct the theoretical curve shown in Fig. 3 from (1). However, since the granular material may have a frequency dependent dielectric function, it is not correct to assume that C_p is constant. We also found that a parallel plate capacitor geometry can be assumed in this experiment, the capacitance is given by

$$C_p = \frac{\varepsilon_o \varepsilon_r A}{d} \tag{2}$$

where ε_r is the dielectric function of the JSC Mars-1 soil simulant, ε_o is the permittivity of free space, $A = 0.420$ mm^2 is the plate area of the capacitor, and $d = 3.5$ mm is the capacitor plate separation. Hence, the volume of the granular soil simulant between the plates of the capacitor is $A\,d$.

The agreement shown in Fig. 3 might imply that it is possible to model a system of loosely packed Martian soil simulant particles as forming the series contacts shown in Fig. 1. While the selected parameter values do provide a good fit to the observed data, the value of C_p does not yield a reasonable value for the dielectric constant ε_r of the Martian soil simulant. It seems more likely that the resistance of the particles must be so large that their effective impedance must be inherently capacitive. Hence, one can ignore the resistance R_p shown in Fig. 2 and set $\omega_p = 0$ in (1), thus resulting in the voltage gain

$$\left|\frac{V_{out}}{V_a}\right| = \frac{G}{1 + \frac{C_A}{C_p}} \tag{3}$$

which is actually frequency dependent because the dielectric function ε_r of the Martian soil simulant depends on the frequency f. If one makes this assumption, then ε_r can be determined from the experimentally measured values of V_{out} by using (2). The dielectric function obtained in this way has the frequency dependence as shown in Fig. 4.

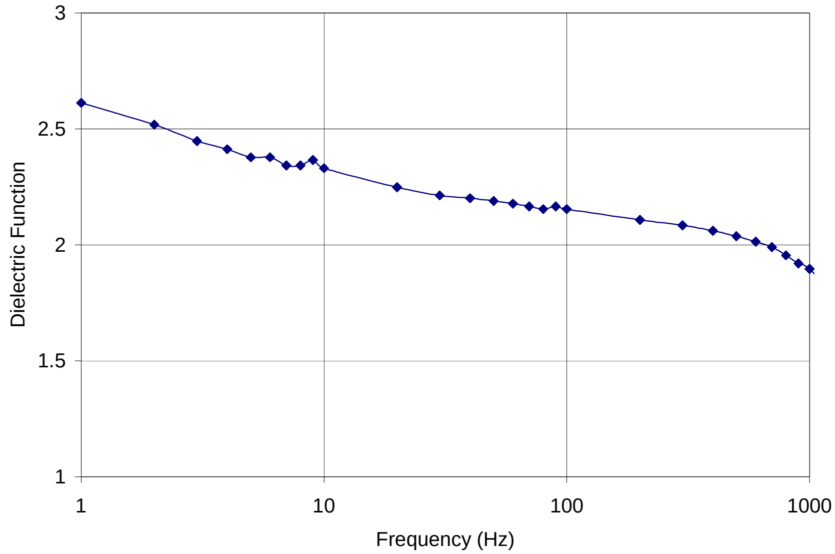

Fig. 4. The frequency response of the dielectric function ε_r of JSC Mars-1 soil simulant as obtained from (2) and (3) using the measured values of V_{out} from Fig. 3.

IV. Conclusions

We have shown that AC impedance measurements can be used to measure the dielectric properties of the Martian soil simulant JSC Mars-1. The data is seen to support a simple model of the granular system in which the effective impedance of the granular material appears to be dominated by the capacitance of the material. We have used our data to determine the dielectric function of JSC Mars-1 soil simulant as a function of frequency, and found that it decreased from 2.6 to 1.9 over the frequency range from 1 Hz to 1 kHz.

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