L-5

METHOD FOR DETERMINING DIELECTRIC PROPERTIES OF SOLIDS FROM MEASUREMENTS ON PULVERIZED MATERIALS

Stuart O. Nelson

U. S. Department of Agriculture, Agricultural Research Service
Richard B. Russell Agricultural Research Center
Athens, Georgia, 30613, U. S. A.

ABSTRACT

A procedure is outlined for determining the dielectric properties of solid materials of known densities from the dielectric properties of pulverized samples measured at a few different bulk densities. Properties for the solid are obtained by extrapolation of functions of the dielectric constant and loss factor that are linearly related to the bulk density of the air-particle mixture.

INTRODUCTION

Often it is difficult to determine the dielectric properties of solid materials because of difficulty in machining samples of some materials to the precise dimensions required for the measurement, because they do not exist in solid form of sufficient size for the measurement, or because, in the case of some minerals, they cannot be obtained in pure form without pulverization and purification. For these reasons, efforts have been devoted to the study of several dielectric mixture formulas for the correlation of the dielectric properties of solid materials with measurements taken on powdered or pulverized materials [1, 2, 3, 4]. This paper describes a method for extrapolation of dielectric properties measurement data on pulverized materials at known bulk densities to obtain the dielectric properties of the solid material at its known density.

METHODS AND PROCEDURES

To illustrate this method, the dielectric constant, ε_r' , and the dielectric loss factor, ε_r'' , the real and imaginary parts, respectively, of the relative complex permittivity, $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$, were measured for a pulverized sample of the mineral goethite[1] at 11.7 GHz with an X-Band, WR-90 waveguide system [5] employing the short-circuited waveguide method of Roberts and von Hippel [6] with computation by the program described previously [7]. Goethite is an iron hydrogen oxide, FeO(OH), commonly found in iron ore deposits and a common constituent of many forms of natural rust. Particle size in the pulverized sample ranged mainly between 10 and 100 micrometers with less than 10 percent of the particles below this range, less than 10 percent above, and none larger than 176 micrometers. The measurements were taken at five different bulk densitites, which were determined by dividing the weight of the pulverized sample by the volume that it occupied in the waveguide sample holder. The density of the solid material was determined by measuring the volume occupied by the pulverized particles in an air comparison pycnometer and dividing the sample weight by that volume. Measured values of ε_r' and ε_r'' of the pulverized goethite sample are shown in Fig. 1.

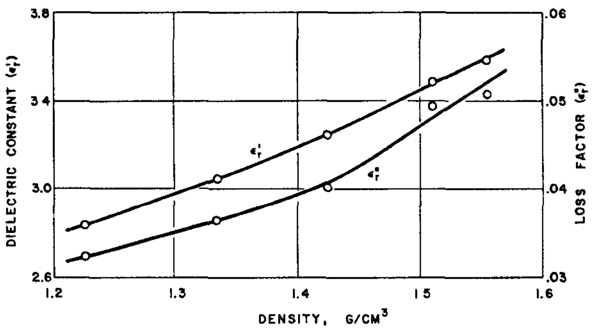

Fig. 1. Density dependence of the dielectric properties of a pulverized goethite sample at 11.7 GHz and 24° C.

It was shown previously that, for an air and pulverized particle mixture, the cube root of the dielectric constant is linear with the density, ρ , of the air-particle mixture [8]. Also, the square

[1] Goethite sample and particle size distribution furnished by U. S. Bureau of Mines, Twin Cities Research Center, Minneapolis, MN.

root of ($\varepsilon_r'' + e$), where e is a small constant, is linear with density. These relationships may be expressed as follows:

$$(\varepsilon_r')^{1/3} = a\rho + b = a\rho + 1 \qquad (1)$$

$$\sqrt{\varepsilon_r'' + e} = \sqrt{e} + \sqrt{c}\,\rho \qquad (2)$$

where a, b, and c are also constants for a specified material at a given frequency. In (1), the intercept, b, is unity, because at zero density for the air-particle mixture there will be no particles, and the dielectric constant of air is 1. Equation (2) follows from the quadratic relationship between the loss factor and density [9]

$$\varepsilon_r'' = c\rho^2 + d\rho \qquad (3)$$

where d is another constant, and

$$e = d^2/4c \qquad (4)$$

For the set of measurement data on ε_r' for the pulverized goethite sample, a linear regression analysis was calculated according to the following model:

$$(\varepsilon_r')^{1/3} = A_o + A_1\rho \qquad (5)$$

and the point (0, 1) was included with the five measured ($\rho, \varepsilon_r'^{\,1/3}$) points for the regression. Thus, the intercept, A_o, was essentially 1 in all instances and equivalent to b of (1), and the value of slope, A_1, was obtained from the regression analysis. This linear relationship then permitted the estimation of the dielectric constant of the material at the density of the solid material as illustrated in Fig. 2, by using the density determined for the solid material by air-comparison pycnometer measurement on the pulverized sample and solving for ε_r' in (5).

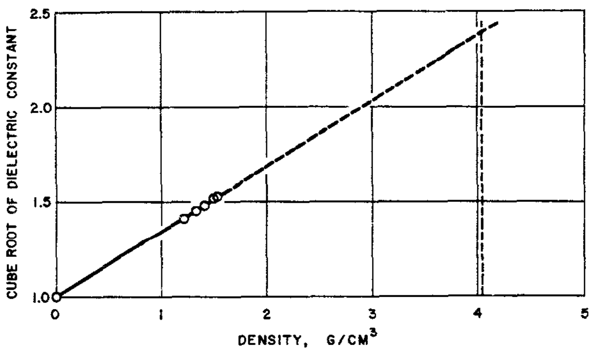

Fig. 2. Linearity of the cube root of the dielectric constant, ε_r', with density for a pulverized goethite sample at 11.7 GHz and 24° C and extrapolation to the density of the solid material (4.04 g/cm³) for estimation of ε_r' of the solid material.

Use of the linear relationship of (2) for estimation of the loss factor, ε_r'', requires a value for the constant, e. The value of e was determined by (4) after first determining c and d of (3) by second-order polynomial or quadratic regression analysis,

$$\varepsilon_r'' = B_o + B_1\rho + B_2\rho^2 \qquad (6)$$

The point (0, 0) was included along with the measured (ρ, ε_r'') points as illustrated in Fig. 3. Inclusion of the (0, 0) point ensures that B_o is essentially zero, and the resulting values of the coefficients B_1 and B_2 correspond to d and c of (3), respectively. Once the values for e and c were known, (2) would provide the estimate for the loss factor of the solid material when the solid material density was used for the calculation. However, a linear regression of $\sqrt{\varepsilon_r'' + e}$ vs. ρ was used to calculate the coefficients,

$$\sqrt{\varepsilon_r'' + e} = C_o + C_1\rho \qquad (7)$$

The extrapolation to solid material density is illustrated in Fig. 4.

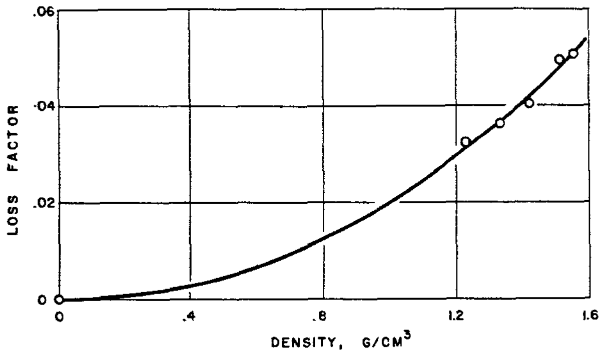

Fig. 3. Second-order polynomial regression line for the dielectric loss factor of a pulverized goethite sample at 11.7 GHz and 24° C.

RESULTS AND DISCUSSION

The values of the dielectric properties for solid goethite at 11.7 GHz and 24° C obtained by this method are 13.7 for ε_r' and 0.33 for ε_r''. Calculation of these values from the measurement data on the pulverized material according to the Landau and Lifshitz - Looyenga formula [2] gave values ranging from 13.2 to 13.9 for ε_r' and from 0.29 to 0.32 for ε_r'' over the five densities measured. This agreement is not surprising, because the linearity of $(\varepsilon_r')^{1/3}$ with density is consistent with the Landau and Lifshitz - Looyenga relationships for dielectric mixtures. Values for ε_r' calculated from the equation of Dube et al., [4] gave values ranging from 11.3 to 12.0.

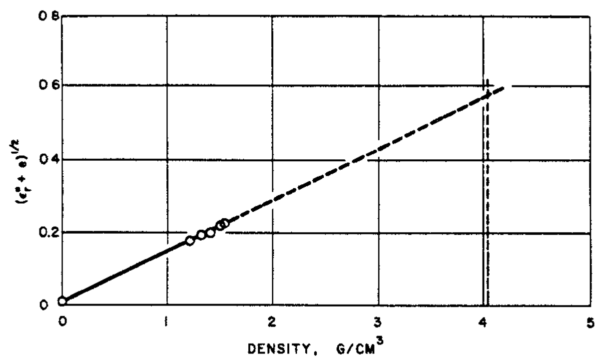

Fig. 4. Linearity of (ε_r'' + e)$^{1/2}$ with density for a pulverized goethite sample at 11.7 GHz and 24° C and extrapolation to the density of the solid material (4.04 g/cm^3) for estimation of the dielectric loss factor, ε_r'' , of the solid material.

As noted previously [8], linearity of the square root of ε_r' with density is consistent with the Kraszewski mixture formula [10]. Extrapolation of the $(\varepsilon_r')^{1/2}$ vs. ρ straight line for the goethite data gave a value of 11.1 for ε_r' of the solid material. Although both the cubic, $(\varepsilon_r')^{1/3}$ vs. ρ , and the quadratic, $(\varepsilon_r')^{1/2}$ vs. ρ , relationships were practically equivalent in predicting the ε_r' values measured for pulverized coal, whole-wheat flour, and whole-kernel wheat [8], the cubic relationship had somewhat better accuracy in predicting those values in the range covered by the measurement data. Therefore the cubic relationship was selected for presentation here. However, the cubic and quadratic relationships have not been carefully compared for accuracy of prediction outside the range of measured values of ε_r' .

Although the relationships represented by (1) and (2) have not been tested with materials of known dielectric properties in the solid and pulverized forms over a wide range of dielectric properties, the relationship for the cube root of ε_r' , when tested for pulverized coal, did yield estimates within 0.1 percent of the measured values over the density range for which samples were measured [8]. However, the error may be much larger for extrapolations outside that range. Nevertheless, this procedure should be useful for estimating the dielectric properties of solid materials from measured data on pulverized samples of the same material.

REFERENCES

1. D. C. Dube and R. Parshad, "Study of Böttcher's formula for dielectric correlation between powder and bulk," J. Phys. D: Appl. Phys., vol. 3, pp. 677-684, 1970.
2. D. C. Dube, "Study of Landau-Lifshitz-Looyenga's formula for dielectric correlation between powder and bulk," J. Phys. D: Appl. Phys., vol. 3, pp. 1648-1652, 1970.
3. A. S. Yadav and R. Parshad, "On the utilization of Böttcher's formula for correct correlation of dielectric constant of powder and bulk," J. Phys. D: Appl. Phys., vol. 4, pp. 822-824, 1971.
4. D. C. Dube, R. S. Yadava and R. Parshad, "A formula for correlating dielectric constant of powder and bulk," Indian J. Pure & Appl. Phys., vol. 9, pp. 719-721, 1971.
5. S. O. Nelson, "A system for measuring dielectric properties at frequencies from 8.2 to 12.4 GHz," Trans. ASAE, vol. 15, pp. 1094-1098, 1972.
6. S. A. Roberts and A. Von Hippel, "A new method for measuring dielectric constant and loss in the range of centimeter waves," J. Appl. Phys., vol. 17, pp. 610-616, 1946.
7. S. O. Nelson, L. E. Stetson, and C. W. Schlaphoff, "A general computer program for precise calculation of dielectric properties from short-circuited-waveguide measurements," IEEE Trans. Instr. and Meas., vol. IM-23, pp. 455-460, 1974.
8. S. O. Nelson, "Observations on the density dependence of dielectric properties of particulate materials," J. Microwave Power, vol. 18, pp. 143-152, 1983.
9. M. Kent, "Complex permittivity of fish meal: a general discussion of temperature, density and moisture dependence," J. Microwave Power, vol. 12, pp. 341-345, 1977.
10. A. Kraszewski, "Prediction of the dielectric properties of two-phase mixtures," J. Microwave Power, vol. 12, pp. 215-222, 1977.