Dielectric properties of black and red soils at microwave frequency

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The real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the complex dielectric constant ($\varepsilon^*$) of soil with varied moisture content have been determined experimentally under laboratory conditions at 9.44 GHz using infinite sample method. The value of $\varepsilon'$ and $\varepsilon''$ first increases slowly and then rapidly with moisture content. From this data, the ac conductivity and relaxation time are also reported. The result shows the change in electrical properties of soil before and after the addition of water. These results provide basis for using ground penetrating radar or other high frequency electromagnetic sensors in the detection of soil moisture content.

Keywords: Dielectric constant, Dielectric loss, Conductivity, Relaxation time

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1 Introduction

The study of dielectric properties of different earth constituents at microwave frequencies is vital as they provide successful interpretation of various remote sensing data. The dielectric constant of soil is a function of moisture content. Microwave emission depends upon the dielectric constant of the soil. Microwave transmission and reflection of moisture-laden brown and black soil using Ku-Band have also been reported. Measurements of dielectric constant and conductivity of soil samples contaminated by diesel oil in the frequency range 2-250 MHz has been reported. The determination of soil water content in coaxial transmission line has been reported. The different methods are used for the study of various electrical properties at X-band microwave frequency. The present study has been undertaken to have an idea of electrical properties of different soils of the Bidar region in Karnataka State. In this paper, the experimentally determined values of the real and imaginary parts of the complex dielectric constant have been shown for soils under study with varied moisture content. From this, the conductivity and relaxation time are determined.

2 Materials and methods

The technique used in the measurement is the infinite sample method. An X-band microwave bench operating at 9.44 GHz in the TE$_{10}$ mode with slotted section and a crystal detector used for measurement of voltage standing wave ratio (VSWR) and the shift of minima are needed in this technique. The complex dielectric constant can be calculated using the relation:

$$
\varepsilon^* = \varepsilon' - j\varepsilon''
$$

$$
\varepsilon' = \frac{1}{1 + \frac{\lambda_\varepsilon}{\lambda_g}^2} \left[ \frac{1}{1 - j \frac{\varepsilon''}{\varepsilon''}} \right]^2 \left[ 1 \right] \frac{\left( r - j \tan[k(D - D_R)] \right)^2}{\left[ 1 - j \frac{\varepsilon''}{\varepsilon''} \right]} \quad \ldots(1)
$$

Separating the real and imaginary part of dielectric constant form Eq. (1), the equation for dielectric constant, $\varepsilon'$ is given by

$$
\varepsilon' = \frac{1}{1 + \frac{\lambda_\varepsilon}{\lambda_g}^2} \left[ \frac{\lambda_\varepsilon}{\lambda_g}^2 \right] \left[ \left( r^2 - E^2 \right) \left( l - r^2 E^2 \right) + (2rE)^2 \right] \ldots(2)
$$

and dielectric loss, $\varepsilon''$ is given by

$$
\varepsilon'' = \frac{\left( \lambda_\varepsilon \right)^2}{1 + \left( \frac{\lambda_\varepsilon}{\lambda_g} \right)^2} \left[ \frac{2rE \left( l - r^2 E^2 \right)}{(l - r^2 E^2)^2 + (2rE)^2} \right] \quad \ldots(3)
$$
where, $\lambda_c$, is cut-off wavelength; $\lambda_g$, guide wavelength; $k$, wave vector; $r$, voltage standing wave ratio (VSWR); and $D$ & $D_R$ the positions of first minima with and without sample connected, respectively. The samples were filled and pressed manually in 40 cm long wave guide, which was terminated with matched load. The soil sample for the present study was taken from Bidar region of Karnataka State. Samples were collected from both irrigated and non-irrigated areas. The physical and chemical properties of the soil were measured at Soil Analysis Laboratory, Department of Agriculture, Govt of Maharashtra at Parbhani. Twelve samples, having different soil textures, physical and chemical properties, were used for the study. Out of these, only two samples are reported.

The dry soil samples were oven dried and wet soil samples were prepared with distilled water. The gravimetric soil moisture content in percentage $W_c$ (%) is calculated using wet ($W_1$) and dry ($W_2$) soil masses using the relation:

$$W_c(\%) = \frac{W_1 - W_2}{W_2} \times 100$$  \hspace{1cm} \ldots(4)

Measurements have been carried out at 9.44 GHz. The experimental set up consist of a 2 K 25 reflex klystron as the microwave source, with maximum output power of 25 mW and frequency range 8.2-12.4 GHz. The source was connected with a broadband isolator with maximum isolation of 30 dB and insertion loss of 1.25 dB to avoid the interference between source and reflected signals. A variable attenuator is connected after the isolator to control the power at desired level. A resonance type frequency meter with high Q-factor (Q~1000) and 2.5 MHz resolution with dip $\geq$ 1 dB was used to measure frequency of the signal. The diode detector with square law characteristics with VSWR better than 2:1 was used. The measurements of $D$, $D_R$, $\lambda_g$ and VSWR were made using a slotted line. The VSWR was determined using double minimum power method. For accurate measurements of minima and VSWR, the probe carriage was equipped with a dial gauge which has 1 mm range with 0.001 mm scale divisions. Accuracy of measurement of real ($\varepsilon'$) and imaginary ($\varepsilon''$) parts of the complex dielectric constant ($\varepsilon*$) is $\pm$ 0.001 and $\pm$ 0.004, respectively.

From the knowledge of dielectric constant and dielectric loss, the ac electrical conductivity and relaxation time are obtained by using the relation$^9,10$:

$$\sigma = \omega \varepsilon'' \varepsilon_0$$  \hspace{1cm} \ldots(5)$$

and

$$\tau = \frac{\varepsilon''}{\omega \varepsilon'}$$  \hspace{1cm} \ldots(6)$$

where, $\omega$, is angular frequency ($f = 9.44$ GHz); $\varepsilon_0$, permittivity of free space ($8.85 \times 10^{-12}$ Fm$^{-1}$)

### 3 Results and Discussion

The constituents of the soil have been listed in Table 1. The variations in the values of dielectric constant and loss with percentage moisture content have been measured and are plotted in Figs 1 and 2 for black and red soil, respectively. Similarly, the electrical conductivity and relaxation time with percentage moisture content are plotted in Figs (3 and 4). It is obvious that the relative permittivity of the soils increase slowly with moisture content initially, this may be due to bi-phase dielectric behaviour of water molecule in soil that have smaller permittivity values as compared to free water molecules below transition point and after reaching a transition point, they increase rapidly. From the study, it is observed that the relation between the dielectric constant and the gravimetric water content is non-linear. This is because for a composite material such as moist soil, the dielectric constant is not a simple

<table>
<thead>
<tr>
<th>Soil</th>
<th>Sand, %</th>
<th>Silt, %</th>
<th>Clay, %</th>
<th>W H C, %</th>
<th>Physical properties</th>
<th>Chemical properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Particle density, g cm$^{-3}$</td>
<td>Apparent density, g cm$^{-3}$</td>
<td>Porosity, %</td>
<td>Volume expansion, %</td>
<td>pH</td>
<td>E C (σ), mS cm$^{-1}$</td>
</tr>
<tr>
<td>Black</td>
<td>1.9</td>
<td>1.3</td>
<td>60.7</td>
<td>63.7</td>
<td>8.97</td>
<td>0.47</td>
</tr>
<tr>
<td>Red</td>
<td>2.0</td>
<td>1.2</td>
<td>51.5</td>
<td>22.5</td>
<td>6.11</td>
<td>0.40</td>
</tr>
</tbody>
</table>
function of the values for the individual components. The ac electrical conductivity ($\sigma$) and relaxation time ($\tau$) show systematic change with increase in moisture content. The dielectric loss is proportional to the ac conductivity. The increase in relaxation time due to increase in moisture content is due to increasing hindrance to the process of polarization. These results are in good agreement with the earlier studies\textsuperscript{2-5}.

4 Conclusions

Based on the above discussion, the following conclusions may be drawn:

1 The laboratory study of dielectric properties of soils with varied moisture, density, temperature, as well as other physical and chemical properties are very important in correlating the data recorded by remote sensing techniques.

2 The existence of bound water in soil-water mixtures significantly affects the electrical properties of mixtures.

3 The relationship between dielectric properties and gravimetric water content is non-linear.

4 The conductivity and relaxation time depends upon the dielectric loss, which represents attenuation and dispersion.

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References


