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Dielectric Characteristics Influenced by Moisture of Various Soil Textures at X-band Microwave Frequencies

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Abstract- — The dielectric response of soils is influenced by multiple factors including electromagnetic frequency, volumetric moisture content, soil composition, internal geometry of components and electrochemical interactions. These effects were characterized using the infinite sample technique to determine the real (ε/) and imaginary (ε//) parameters of the complex permittivity (ε*) of soils with different moisture contents. Measurements were conducted using an X-band microwave test bench operating at 9.44 GHz in the TE10 mode with a crystal detector and a slotted section. This configuration enables precise determination of dielectric parameters for bulk soil specimens. The observed behavior of ε/ and ε// shows an initially modest rise with increasing moisture followed by a pronounced increase at higher water contents, reflecting the strong influence of water on dielectric properties at microwave frequencies. Derived quantities such as a.c. electrical conductivity and dielectric relaxation times were also extracted from the permittivity data. The results demonstrate significant alterations in the electrical properties between dry and moist soils, with notable dependence on soil texture. These observations aid in interpreting ground-penetrating radar signatures and in the calibration of both active and passive microwave remote sensing systems.

Keywords: Microwave, Dielectric permittivity, Dielectric loss, conductivity, Relaxation Time.

I. INTRODUCTION

Soil moisture is a critical parameter influencing agricultural productivity, hydrological processes, and environmental monitoring. Microwave remote sensing techniques have gained significant attention for soil moisture estimation because microwave signals are highly sensitive to the dielectric properties of soil. The dielectric characteristics of soil depend mainly on moisture content, soil texture, bulk density, and frequency of operation. At X-band frequencies (8–12 GHz), variations in soil moisture significantly affect the dielectric constant, enabling accurate assessment of soil conditions through radar and remote sensing applications.

Different soil textures, such as sandy, loamy, and clayey soils, exhibit distinct dielectric responses due to their varying water retention capacities. Therefore, understanding the relationship between soil moisture and dielectric properties across different soil textures at X-band frequencies is essential for improving soil moisture retrieval models and enhancing the accuracy of microwave-based sensing systems. This study investigates the influence of moisture content on the dielectric characteristics of various soil textures operating in the X-band microwave region.

II. PROBLEM STATEMENT

Microwave remote sensing is fundamentally according to electromagnetic wave interaction with heterogeneous geophysical materials. The dielectric characteristics of soils are governed by their composition and physical characteristics such as porosity, density, temperature and moisture content. Consequently, microwave dielectric characterization of soils and its correlation with physicochemical characteristics play an important role in radar and remote sensing applications.

A number of studies have analyzed soil dielectric behavior using different experimental techniques. Chaudhari and Shinde [1] examined soils from the geologically diverse Bidar district of Karnataka at X-band frequency using the infinite sample method. The real (ε/) and imaginary (ε//) components of the dielectric complex permittivity (ε*) measured using the coaxial probe technique over the 0.3–1.3 GHz frequency bands have been documented [2]. Srivastava and Mishra [3] further investigated soil dielectric characteristics at X-band frequency employing the infinite sample method.

Narasimha Rao and Raju [4] established that the dielectric permittivity of soil strongly depends on moisture content, while Calla et al. [5] analyzed the estimation of soil dielectric constant based on soil texture. Curtis et al. [6] reported laboratory-measured dielectric properties and corresponding electromagnetic wave propagation parameters for a broad range of soil textures at 100 MHz. Additionally, Puri et al. [7] investigated the dielectric behavior of red soil in the 12–18 GHz frequency range and Ku-band microwave transmission and reflection studies of moisture-rich brown and black soils have also been reported [8].

III. EXPERIMENTAL SETUP

The present investigation involved systematic measurements by using an X-band microwave bench operating at 9.44 GHz in the TE10 mode. A 2K25 reflex klystron, operating over the frequency range of 8.2–12.4 GHz with a largest output power of 25 mW, was used as the primary microwave source. To mitigate signal coupling and back-reflection effects, a broadband isolator rated at 30 dB isolation was deployed in the experimental configuration, followed by a variable attenuator for power control.

The operating frequency was measured using a resonance-type frequency meter, while voltage standing wave ratio (VSWR) and measurement of distance were performed using a slotted line section. Samples were manually compacted and compacted in a 40 cm long rectangular waveguide terminated with a matched load. The real (ε/) and imaginary (ε//) components of the dielectric complex permittivity (ε*) were determined using the infinite sample technique described by Altshuler [15].

Materials and Methods

An X-band microwave bench operating at 9.44GHz in the TE10mode, equipped with a slotted line section and a crystal detector, was employed for dielectric measurements. A 2K25 reflex klystron was employed as the microwave source used in the experimental arrangement, operating for the frequency range of 8.2–12.4 GHz with a largest output power of 25mW.

To reduce signal coupling and back-reflection effects, a broadband isolator (30 dB isolation, 1.25 dB insertion loss) was integrated into the transmission path between the source and the measurement section. A variable attenuator was connected downstream of the isolator to precisely control the microwave power level. The signal frequency was determined using a resonance-type frequency meter, while voltage standing wave ratio (VSWR) and spatial measurements were obtained using the slotted line technique. Soil samples were manually compacted and compacted into a 40 cm long microwave guide terminated with a matched load.

The respective real and imaginary parts (ε/ and ε//) of the complex dielectric permittivity (ε*) are measured using asymptotically large sample technique described by Altshuler [15], using the following equation $\varepsilon^{*} = \varepsilon^{/} - j\varepsilon^{//}$

$$\varepsilon^{*} = \frac{1}{1+\left[\frac{\lambda_c}{\lambda_g}\right]^2} + \frac{1}{1+\left[\frac{\lambda_g}{\lambda_c}\right]^2}\left[\frac{r - j\tan[k(D-D_R)]}{1 - jr\tan[k(D-D_R)]}\right]^2 \text{.......(1)}$$

Here, and denote the cut-off wavelength, guide wavelength and wave vector, respectively; r represents the voltage standing wave ratio (VSWR), while D and DR are the positions of the first voltage minima with and without the sample. The parameters D, DR and were measured using a slotted line and the VSWR was determined by the double-minimum power method. Accurate determination of VSWR and minima shift is essential; therefore, the probe mount was fitted with a gauge of 1 µm least count.

From the measured dielectric permittivity and dielectric loss, electrical parameters such as conductivity were subsequently evaluated [13-14].

$$\sigma = \omega\varepsilon_0 \varepsilon^{//} \text{..........(2)}$$

The relaxation time from the equation

$$\tau = \frac{\varepsilon^{//}}{\omega\varepsilon^{/}} \text{...........(3)}$$

Where, ω is angular frequency, ε_0 is constant of free

Space ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m)

The soil samples analyzed in the current study, samples were collected from agricultural fields in the Nashik region of Maharashtra, India, covering both irrigated and non-irrigated sites. Physico-chemical analysis of the samples was done at the Soil Analysis Laboratory, Department of Agriculture, Government of Maharashtra, Parbhani. Ten soil samples with varying textures and physical and chemical properties were selected for detailed analysis.

The gravimetric soil moisture content in percentage W_C (%) is calculated using wet (W_1) and dry (W_2) soil masses as given by the following relation

$$W_c(\%) = \frac{W_1 - W_2}{W_2} \times 100..........(4)$$

Setup of microwave X-band for measurement of dielectric properties.

4.28: Physicochemical properties of Soil Samples at Nasik region

Table 1
Physical Characteristics

Soil	Black	Red
Sand %	8.9	6.8
Silt %	49.45	37.5
Clay%	41.65	55.7
W.H.C%	77.7	57.8
Porosity	60.7	51.5
Volume Expansion	63.7	22.5

Table 2

Chemical Characteristics

Soil	Black	Red
PH	8.47	6.11
E.C. mS/cm	0.47	0.4
Organic Carbon	0.92	0.22
P_2O_5 kg/ha	31.14	27.52
K_2O kg/ha	454.27	331.97
Ca %	29.19	25.02
Mg %	19.73	18
Na %	0.6	0.47
$CaCO_3$ %	6.62	4.75

RED SOIL

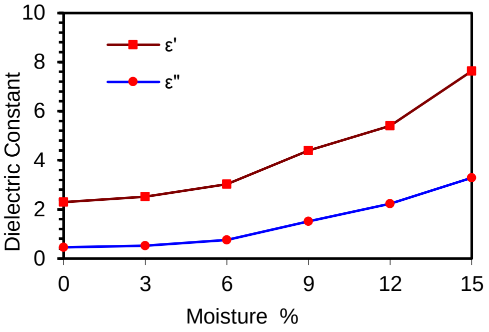

Fig. 1

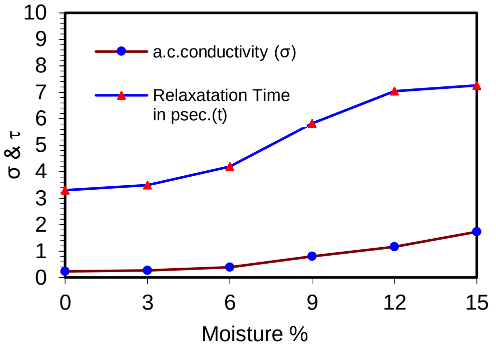

Fig. 3

BLACK SOIL

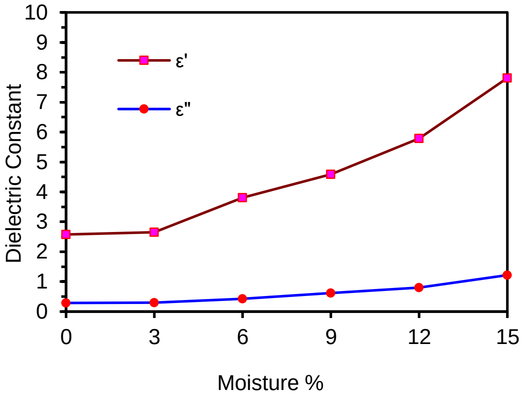

Fig. 2

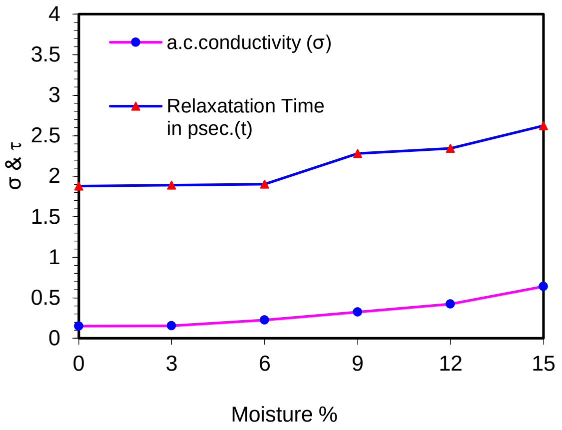

Fig. 4

IV. FINDINGS AND INTERPRETATION

The physicochemical properties of the textural classification of the soil samples are shown in Tables 1 and 2. The measured variations of dielectric permittivity and dielectric loss with gravimetric moisture concentration for red and black soils are presented in Figs. 1 and 2, respectively. The dependence of a.c. electrical conductance and dielectric relaxation time on moisture content is presented in Figs. 3 and 4. It is found that the relative constant of soil initially progressively enhances with moisture content, succeeded by a rapid rise beyond a transition point. This behavior can be associated with the bi-phase dielectric nature of water molecules in soil, wherein bound water exhibits lower permittivity compared to free water below the transition point. Consequently, the correlation between dielectric constant and gravimetric moisture content is non-linear. This nonlinearity arises because, in a composite medium such as moist soil, the effective dielectric constant is not a simple additive function of its individual constituents.

Soil texture is found to impact the electrical properties significantly. The dielectric permittivity and dielectric loss values are greater for red soil than black soil, which may be attributed to the higher content of silicates and calcium carbonate in black soil. Furthermore, the a.c. electrical conductivity (σ) and relaxation time (τ) exhibit systematic variations with increasing moisture content. The a.c. conductivity is directly proportional to dielectric loss, indicating that charge transport occurs predominantly through displacement current. The observed increase in relaxation time with moisture content is attributed to enhanced hindrance to polarization processes.

Findings

Soil moisture significantly affects the dielectric response of soil–water systems. A pronounced non-linear dependence of dielectric properties on gravimetric water content is observed. Laboratory measurements of soil dielectric characteristics under controlled moisture conditions, together with corresponding physicochemical properties, are essential for establishing robust correlations with field-scale data obtained through remote sensing techniques.

The AC electrical conductivity and relaxation time are mainly governed by dielectric loss, which reflects attenuation and dispersion processes in the medium. These results support the applicability of ground-penetrating radar and demonstrate the relevance of the extracted dielectric parameters for both passive and active microwave remote sensing sensors. Moreover, the sensitivity of dielectric characteristics to soil physical and chemical constituents indicates their potential use in soil fertility prediction. However, further systematic experimental investigations are required to decouple and quantify the significance of individual constituents on the observed dielectric behaviour.

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