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Effect of Temperature on the Dielectric Constant of Urea-Doped Soil

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Abstract

Soils are collected and dried for 12 hours at room temperature using a muffle furnace and ground to form powder. The powder is mixed with polyvinyl alcohol solution and formed into a thin pellet having a diameter of 3cm and a thickness of 1.02 mm using a Hydrostatic Press. Dielectric constants are measured for different temperatures using the LCR meter SM6019. The variation of the dielectric constant with frequency and temperature has been plotted for both the real and imaginary components. Dielectric constant at low frequency is high but decreases with the decrease of frequencies and is almost constant at higher frequencies. This shows that the dipoles and space charges are no longer able to follow the rapidly alternating electric field, leaving only electronic and ionic polarisation contributions at high frequencies. The result signifies how urea affects the dielectric constant of soil allows for the development of more accurate soil moisture and nutrient sensors.

Keywords: Dielectric constant, Urea, Space charge, Electric dipole, Polarisation, Alternating field.

Introduction:

Soil is a multi-component framework comprising solid, fluid and vaporous stages, and living organisms. The solid phase of soil consists of both inorganic and natural parts. The organic components present in much smaller quantities than the inorganic components may significantly alter the properties of soil. The electrical characteristics of every material are different to each other and are dependent on its dielectric properties. The dielectric constant is a measure of the response of a system to an applied field. These properties provide valuable information which helps researchers utilise these data in their design or for the purpose of material characterisation, or for monitoring quality.

Dielectric properties of the material depend on the activity of permanent electrical dipoles, ionic conduction and the degree of dipole alignment with the applied time-varying electric field. In the case of non-homogeneous material such as soil, the dielectric properties are affected by the composition of the material, which affects the molecular movement. The microwave soil dielectric measurement uses absorption of microwaves corresponding to rotational energy of molecules when an electromagnetic field is applied to the dielectric material; energy is dissipated in these materials as a result of the dielectric relaxation process. The dielectric properties of soil are a function of its naturally available chemical constituents, such as carbon, sodium, potassium, iron and physical properties such as sand, silt, and clay [1]. Dielectric behaviour of dry soil of different districts of Haryana (India) at 5.8 GHz. Dry soil of two districts of Haryana are collected and studied using the Waveguide cell technique [2]. Vivek Y reported that the relative permittivity of the soil increases slowly with moisture content initially and rapidly after reaching the transition point [3]. Gandani D.H *et a*l use LCR metre in the study of dielectric properties of wet and fertilised soil at radio frequencies. It is observed that dielectric constant ($\varepsilon^{/}$)and dielectric loss ($\varepsilon^{//}$) increase with increase in concentration of fertiliser [4]. Rajeev K and Anupamdeep studied the soil of the Indo-Gangetic region, and it is concluded that the dielectric constant increases with gravimetric moisture content and then rapidly after a fixed frequency [5]. Sahu V *et al.,* in the study of dielectric and physicochemical properties of soil, show that dielectric properties depend on physical and chemical characteristics of the various soils as well as nutrient concentration [6]. Patel *et a*l measured the complex dielectric constant of soil of Gujarat at X- and C-band microwave frequencies and found that the dielectric constant of soils increases with moisture content [7]. Black soils are prevalent in Manipur, contributing significantly to the region's agricultural landscape. Understanding the electrical properties of sandy soils, particularly the dielectric constant, is essential for effective soil management and environmental monitoring in Manipur.

This paper reports an experimental investigation into the frequency dependence of the dielectric constant of sandy soils in Manipur to enhance our understanding of their electrical behaviour.

Experimental:

Black soil samples were collected from the Bishnupur district of Manipur and dried for 12 hours at room temperature, using a muffle furnace to remove moisture and ensure uniformity. The dried soil was then pulverised into a fine powder and mixed with a polyvinyl alcohol solution. Thin pellets with a diameter of 3 cm and a thickness of 1.02 mm were formed using a hydrostatic press. Dielectric constant measurements were conducted using an LCR meter (SM6019) across a frequency range from 100 Hz to 25,000 Hz for a different range of temperature from 303K to 373K. The measurements were repeated multiple times to ensure accuracy and reliability.

The dielectric constant was measured from the relation.

$$\varepsilon_r^1 = \frac{Cd}{\varepsilon_0 A}$$

And the complex permittivity

$$\varepsilon^* = \varepsilon_r^{11} - j\varepsilon_r^{11}$$

Where ε_r^1 is the real permittivity, and ε_r^{11} is the imaginary permittivity

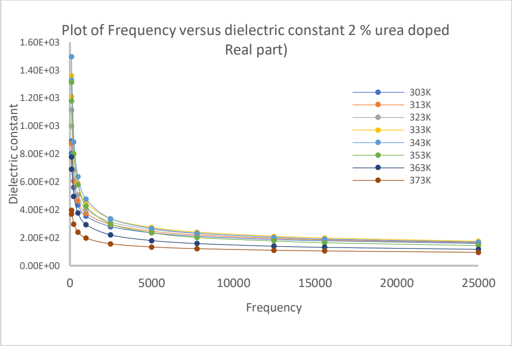
The dissipation factor is given by

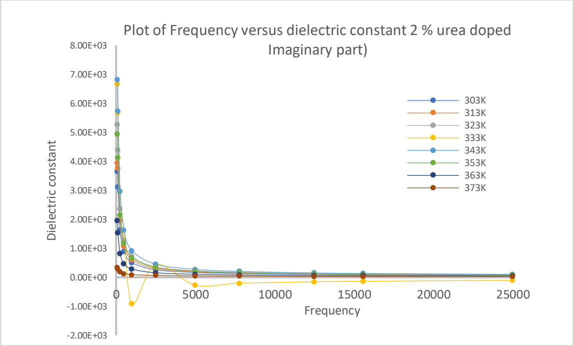
$$\tan ø = \frac{\varepsilon_r^{11}}{\varepsilon_r^1}$$

where ø is the phase angle

Result and Discussion:

The frequency dependence of the dielectric constant of the 2% urea-doped soil shows a typical dispersive behaviour for heterogeneous and polar materials. In the real part of the dielectric constant (ε_r'), very high values are observed at low frequencies for all temperatures from 303 K to 373 K. This large ε_r' at low frequency is mainly attributed to space-charge or interfacial polarization (Maxwell–Wagner–Sillars effect)[8], which arises due to the accumulation of charges at grain boundaries, pores, and interfaces between soil particles, moisture, and urea molecules [9]. As frequency increases, ε_r' decreases sharply and then gradually attains a nearly constant value at higher frequencies. This occurs because dipoles and space charges are no longer able to follow the rapidly alternating electric field, leaving only electronic and ionic polarisation contributions at high frequencies [10].





The effect of temperature is also evident. At a given frequency, ε_r' decreases with an increase in temperature. With rising temperature, thermal agitation disrupts the alignment of dipoles and reduces the effectiveness of interfacial polarisation, leading to a lower dielectric constant [11]. Additionally, enhanced charge mobility at higher temperatures reduces charge accumulation at interfaces, further suppressing ε_r'.

The imaginary part of the dielectric constant (ε_r'') represents dielectric loss and energy dissipation within the material. ε_r'' is very high at low frequencies and decreases rapidly with increasing frequency for all temperatures. This indicates dominant conduction loss and space-charge polarisation at low frequencies, where charge carriers can migrate over longer distances [12]. At higher frequencies, the reduced ε_r'' signifies lower energy loss as charge carriers fail to respond to the applied field. The decrease of ε_r'' with increasing temperature suggests reduced polarisation loss and a change in relaxation dynamics, although some low-frequency anomalies may arise due to electrode polarisation or experimental limitations [13]. Overall, the results confirm that urea-doped soil behaves as a lossy dielectric with strong frequency and temperature dependence governed by interfacial polarisation and charge transport mechanisms.

As ε_r'' is directly linked to energy loss and charge transport, which are far more sensitive to frequency than polarization storage, the imaginary part of the dielectric constant (ε'') appears much steeper or “stiffer” with frequency than the real part (ε_r'), in fact ε_r' represents the ability of the material to store electrical energy through polarization mechanisms such as dipolar, ionic, and interfacial polarization [8]. As frequency increases, these polarisation mechanisms gradually fail to follow the applied field, so ε_r' decreases smoothly and then saturates at high frequency, where only fast electronic polarisation remains [14]. Since urea-doped soil is a heterogeneous system, in such a system, dielectric loss arises mainly from charge carrier motion, hopping conduction, and space-charge accumulation. At low frequencies, charge carriers have enough time to migrate over long distances and accumulate at grain boundaries, pores, and electrode interfaces, producing very large losses. As frequency increases, this long-range motion is suddenly suppressed, leading to a rapid drop in ε_r''. Because conduction and interfacial losses collapse much faster than polarisation storage, ε_r'' shows a much sharper, stiffer frequency dependence [15].

In short, the stiffer the imaginary part is, the more energy dissipation mechanisms in the soil are highly frequency sensitive, while energy storage mechanisms evolve more gradually. This nature is a clear signature of space-charge polarisation and conduction-controlled dielectric loss in urea-doped soil systems.

Conclusions:

The dielectric behaviour of urea-doped soil has important practical implications in agriculture, geophysics, and environmental monitoring. In precision agriculture, knowledge of the frequency and temperature-dependent dielectric properties helps in the accurate estimation of soil moisture, nutrient content, and fertiliser distribution using dielectric and electromagnetic sensing techniques. Since urea significantly alters the dielectric response, these results can be used to calibrate soil sensors for real-time monitoring of fertiliser application and nutrient efficiency.

In the study of geophysical and geotechnical applications, dielectric data are valuable for interpreting ground-penetrating radar (GPR) and other electromagnetic survey results. Understanding how urea doping and temperature influence ε_r' and ε_r'' improves subsurface characterisation of fertilised agricultural fields. The lossy nature of the soil at low frequencies also provides insight into energy dissipation mechanisms relevant to soil heating and electro-remediation techniques.

Thus, dielectric studies are useful in environmental science for assessing soil quality and contamination, since changes in dielectric properties can indicate chemical amendments or pollutant presence. In a broader sense, the results contribute to the design of soil-based dielectric materials and models for predicting soil–fertilizer–moisture interactions under varying climatic conditions.

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Conflicts of Interest: The authors declare no conflict of interest.

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