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Full Length Research Paper

In situ measurement of soil dielectric permittivity of various soil types across the climatic zones of Nigeria

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The increasing use of microwaves and millimeter waves in various fields of human endeavor such as communications, radar, medicine, biology, agriculture, industrial processes and civil engineering demands accurate data on the dielectric properties of materials. For instance, field density and soil water content are used as a quality control or quality assurance criterion in flexible pavement systems, embankments, canals, earth dams, reinforced earth systems and roadways. This has led to researches into the dielectric properties of porous materials such as soils and rocks. This work has been undergone because of the dearth of data using the *in-situ* method of estimation of soil electrical parameters from the tropics most especially Nigeria and as well as to optimize analysis of soil conditions for enhanced quality and yield of turf and crops. In this paper, *in-situ* measurement of soil parameters such as soil dielectric permittivity, soil volumetric moisture content and soil temperature of various types of soil has been made across the climatic zones of Nigeria using Davis Wireless Vantage Pro2 equipment at a fixed frequency of 928 MHz. The result of this study reveals that soil volumetric moisture content is the dominant factor that influences soil electrical characteristics.

Key words: *In-situ*, dielectric, permittivity, propagation, dispersion.

INTRODUCTION

Numerous measurement techniques have been undertaken to determine the electrical properties of soils. Soils are 3 - phase porous materials consisting of solid particles and voids filled with water and/ or air. Soil properties are dispersive, but when different types of soils are examined at a constant frequency, many factors are discovered to influence the electrical characteristics of this mineral, water, and air mixtures (Curtis and Narayanan, 1998; Dante et al., 2005).

The water in the soil provides the means of dissolving salts in the soil so as to create ions that contribute to electromagnetic losses through low frequency ionic conduction. The dipole nature of the water molecules is also a factor that enhances the soil, the capacitive nature of the soil- water- air mixture and this is reflective in the real part of the dielectric constant. Hence among the factors that influences the electrical behavior of soil (soil volumetric moisture content, soil composition, density of soil solid portion, and temperature), soil volumetric moisture content is the dominant factor (Peplinski et al., 1995; Seker and Abatay, 2005; Seyfried and Grant, 2007). The telemetry method of *in-situ* measurement of soil volumetric moisture content employed here using Davis wireless instrument provides an accurate estimation of soil dielectric permittivity because the procedures does not require the removal of the soil; hence, the subsurface structure of the soil is not disturbed. This work has been undergone because of the dearth of data using the *in-situ* method of estimation of soil electrical parameters from the tropics most especially Nigeria and as well as to optimize analysis of soil conditions for enhanced quality and yield of turf and crops.

THEORECTICAL BACKGROUND

The interaction of electromagnetic energy with matter is affected by the characteristics of the material and by the frequency of the electromagnetic energy. Frequency dependent dielectric properties can be characterized in terms of losses of energy due to relaxation mechanisms

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that operate at different frequencies. The relaxations are caused by different forms of atomic or molecular-scale resonance. In a soil mixture, the relaxation mechanisms may be attributed to the solid material and the pore water. The dielectric permittivity ε^* is a complex function with real and imaginary components. It is defined as

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

where j is the square root of -1

The real part (ε') is often expressed as the relative permittivity (ε_r) or dielectric constant and it is the ratio of the electric field storage capacity to that of free space. It represents the capacitive behaviour or polarizability of the material. The imaginary part (ε'') of the dielectric permittivity is expressed in terms of dielectric losses, which include dispersive losses, free water relaxation and bound water relaxation losses. ε'' is called the loss factor that represents the energy losses due to polarization and conduction.

In permittivity measurement, losses due to polarization and conduction are referred to as effective imaginary permittivity and it is defined as

$$\varepsilon''_{eff} = \varepsilon'' + \frac{\sigma}{\varepsilon_0 \omega} \quad (2)$$

σ is zero – frequency current (DC) conductivity and ω is the angular frequency ($\omega = 2\pi f$) and f is the frequency.

Dielectric constant is a frequency dependent variable and decreases with increasing frequency. At frequencies below 1.5 GHz, the dielectric permittivity (ε'), is only weakly frequency dependent (Topp et al., 1980) while dielectric losses are generally low. At frequencies below 50 MHz, ε'' depends strongly on soil type, and at frequencies of 1 to 1.5 GHz, the dielectric losses increase with increasing water content (Roth et al., 1990, Portella et al., 2006). When an electric field is applied to a medium, some charges (positive and negative) are bound, but they can move locally relative to each other. This movement results in a polarized medium. The polarizability of the medium is represented by permittivity.

Polarization refers to the direction of the electric field in an electromagnetic wave. As an example, a wave whose electric field is oscillating in the vertical direction is said to be polarized in the vertical direction. Hence, permittivity is a measure of the extent to which the electrical charge distributed in a material can be polarized by the application of an electric field.

Time-varying electromagnetic fields generate electro-magnetic waves. The propagation of electromagnetic waves through geo-materials depends on the electrical conductivity, (σ), dielectric permittivity, (ε), and magnetic permeability (μ) properties of the medium. These parameters are frequency dependent because the wave excites the material at diverse time scales yielding different electromagnetic mechanisms within the material.

The dielectric permittivity response of soils depends on the mineral properties, the volumetric water content and the concentration of cationic species (salts). Most soils are nonferromagnetic, hence it is reasonable to assume that the magnetic permeability of the soils equals the magnetic permeability of free space (μ = 1). The relative dielectric permittivity ε_r is a complex number expressed as:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_o} \quad (3)$$

ε is the dielectric permittivity and ε_o is permittivity of free space ($8.85 \times 10^{-12}\ Fm^{-1}$).

Dielectric permittivity can be used to evaluate the speed of wave propagation in a material. For nonferromagnetic materials, electromagnetic wave speed (V) (Santamarina and Fam, 1997) is

$$V = \frac{c}{\sqrt{\frac{1}{2}.\left[\varepsilon' + \sqrt{\varepsilon'^2} + (\frac{\sigma}{\omega.\varepsilon_o})^2\right]}} \quad (4)$$

where c is the speed of light in vacuum (3.0×10^{-10} ms^{-1}), ε' is the frequency dependent real component of the dielectric permittivity, ω is the angular frequency and σ is the electrical conductivity.

Equation 4 shows the electromagnetic wave speed variation with real relative permittivity as a function of water content present in the soil and electrical conductivity as a function of the dissolved salt in the pore fluid.

Topp et al. (1980) carried out detailed research works to relate soil volumetric moisture content with relative dielectric permittivity and came out with the equation:

$$\varepsilon_a = 3.03 + 9.3\theta_v + 146\theta_v^2 - 76.7\theta_v^3 \quad (5)$$

θ_v is soil volumetric moisture content and ε_a is relative dielectric permittivity.

Equation 5 forms the basis of analysis of all the data acquired during the course of this work.

METHODOLOGY

The measurement sites for this research work spanned some selected towns and cities in the climatic zones of Nigeria. The locations were selected based on parameters like the nature of the

soil, seasonal variation, general geological variation, coastal effect, climate and vegetation. The study area covers about 9.1 × 10^5 km^2 lying between longitudes2°30′and 14°30′ east of Greenwich and between latitudes 4°30′ and 14°0′ north of the equator. The selected towns and cities used for this study are Port Harcourt, Lagos, Igbokoda, Akure, Ikirun, Ilorin, Offa, Jos, Kaduna, Kano, Maiduguri and Enugu.

The dielectric permittivity method uses Davis Wireless Vantage Pro2 transmitter equipped with a solar panel (with an alternative battery source) and the wireless console (receiver). The transmitter is equipped with soil moisture sensors and soil temperature sensors for measuring soil moisture content and soil temperature respectively which were sent to a vantage Pro2 console (receiver). The console was connected to a computer, through which the stored data were downloaded.

This method provides an accurate measurement of soil moisture content, soil temperature, pressure, and in- humidity. By this method, the sensors were positioned in the soil and the console was placed in a secured place of about150 to 200 m line of sight to the transmitter containing the sensors. The signals from the sensors were transmitted to the receiver (console) and then stored in a data logger. The measured data were logged by the data logger for a time interval of 15 min depending on the prevailing atmospheric condition of the locations of measurement. From the data collected, dielectric permittivity values were computed for the different locations visited in the course of this work. The results obtained were analyzed and used to predict how soil electrical parameters could influence radio wave propagation (communication), engineering, geo-technics and precision agriculture in the climatic zones of Nigeria.

RESULTS

Here, some of the results obtained from the field measurement of soil dielectric permittivity across the climatic zones in Nigeria are presented. In each of the cities visited, two sites were sampled for data acquisition. The results from Port Harcourt ranged the values of relative permittivity between 7.80 and 9.50, while the values of volumetric moisture content ranged between 0.00 and 0.19 m^3m^{-3}. The results show that as moisture content increases, relative permittivity increases. For all the locations in the coastal zone, permittivity values ranged between 7.50 and 10.00 with corresponding increase in moisture content.

All the locations of study in the forest zone have a gradually increasing value of relative permittivity as the moisture content increases even though the increase is not linear.

Variations of relative permittivity with volumetric moisture content in the Guinea Savanna zone, Sudan Savanna zone and Sahel Savanna zone are not so much different from other zones, except that these zones have reduced values of moisture content and hence lower values of permittivity.

DISCUSSION

When the relation between water content and permittivity is being established in this work, volumetric rather than gravimetric water contents were used, since it is the number of dipole moments per unit volume that determines the contribution of water content to dielectric polarization. Results obtained from all the locations visited across the climatic zones of Nigeria revealed that the values of relative permittivity ranged between 3.03 and 10. This may be due to the fact that the subsurface structure of the soil has not been disturbed. The permittivity value 3.03 is for a very dry soil and about 10.00 for a very wet soil. These values are an improvement over the results obtained in literatures that put the values between 3 and 8 (Dante et al., 2005). The values of relative permittivity were higher in the coastal and the forest zones when compared to the savanna zones of Nigeria. In most of the locations in the savanna zones, the values of permittivity were from about 3.03 and increased to about 9.00 at the peak of the rainy season (Figures 7, 8 and 10). The southern Guinea Savanna zone that is not as dry as the Sudan and Sahel savanna zones in term of water recharge in the soil through rain had their permittivity values ranging between 4.00 and 9.00 (Figures 11 and 12). Figure 10 shows the relationship between relative permittivity and moisture content in the Northern Guinea Savanna zone with values ranging from 3.03 to about 7.50. This impress further the contribution of moisture content to soil electrical parameters: The higher the moisture content, the higher the permittivity value. In the coastal and forest zones, the values were from 6.50 or as high as 7.80 in some locations and it increased to about 10.00 (Figures 1, 2, 3 and 6). For instance, in Enugu, the values ranged between 7.80 and 10.50 at the peak of the rainy season (Figure 4). Akure, a location in the forest zone has fairly different values of permittivity ranging between 3.03 and

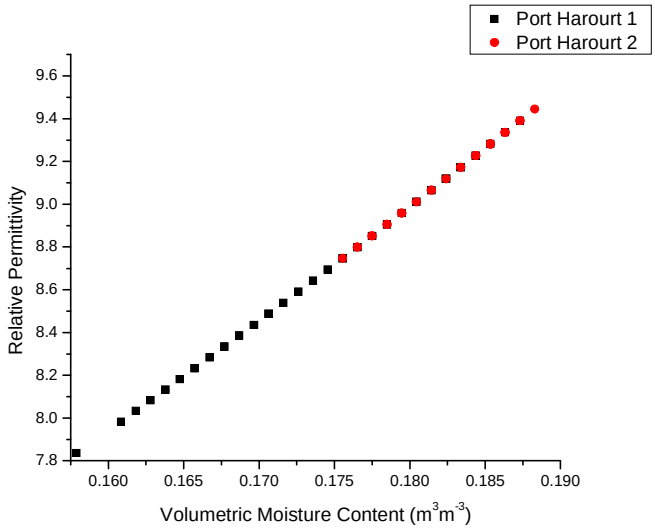


Figure 1. Permittivity against moisture content (Port Harcourt-Coastal Swamps Zone).

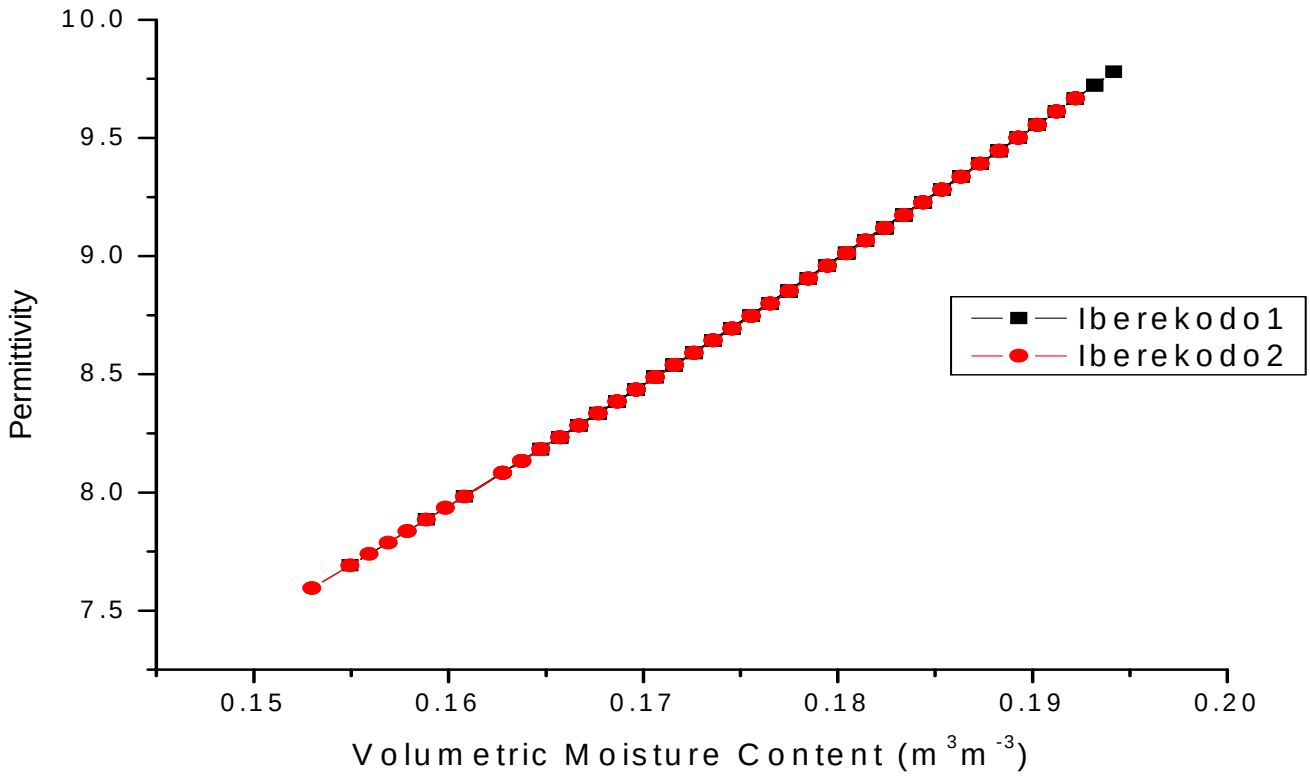


Figure 2. Permittivity against moisture content (Iberekodo, Lagos- Coastal Swamps Zone).

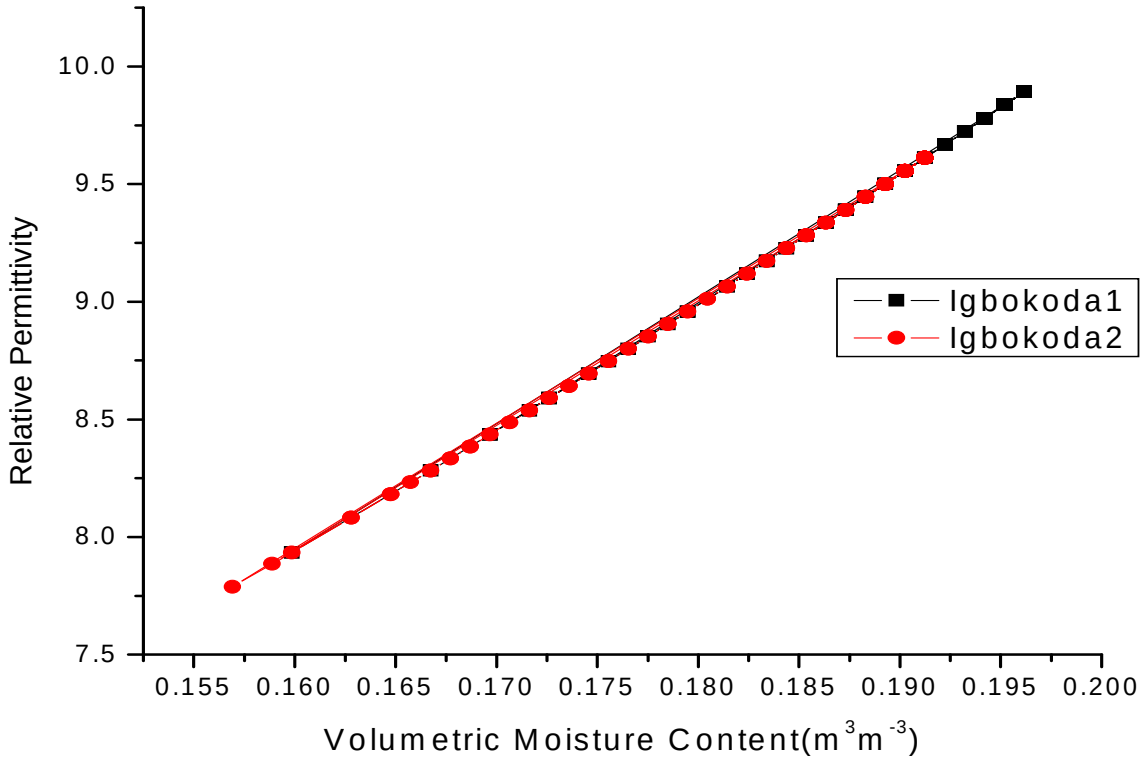


Figure 3. Permittivity against moisture content (Igbokoda- Coastal Swamps Zone).

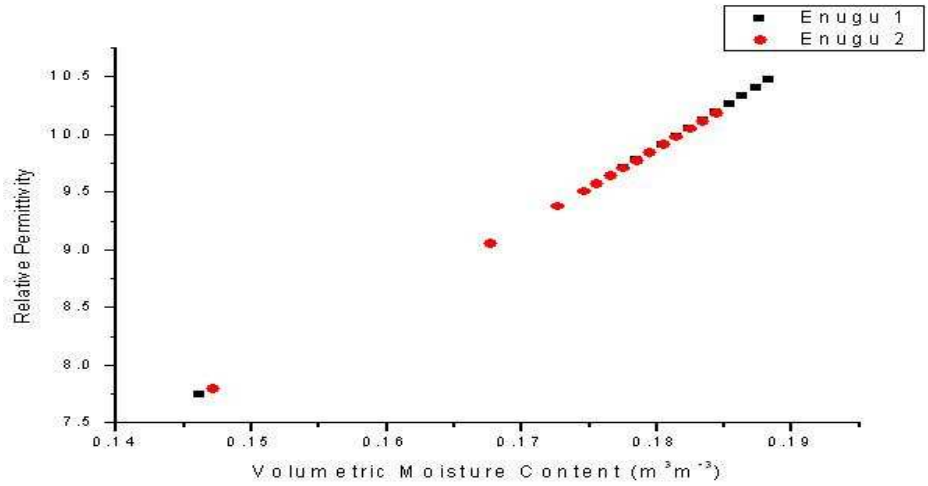


Figure 4. Permittivity against moisture content (Enugu- Forest Zone).

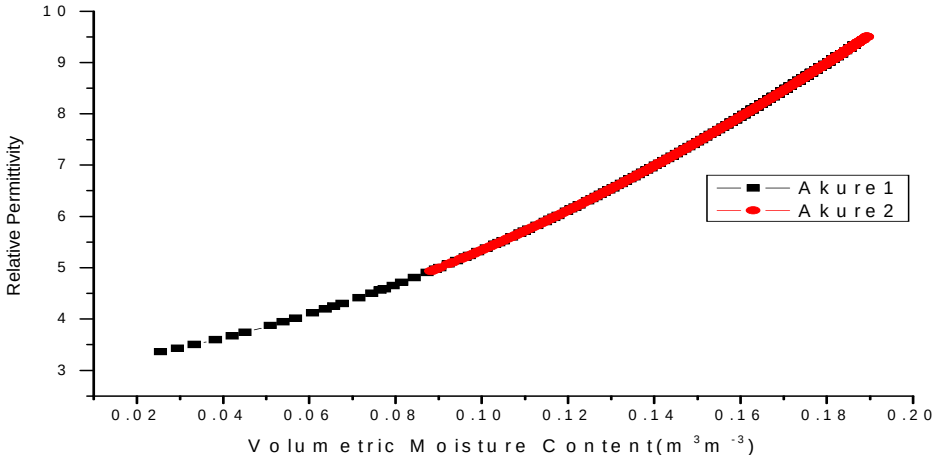


Figure 5. Permittivity against moisture content (Akure- Forest Zone).

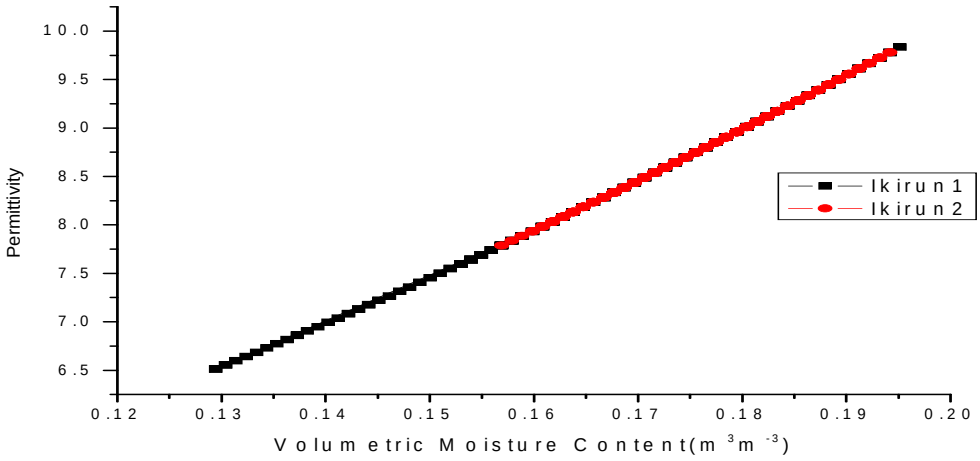


Figure 6. Permittivity against moisture content (Ikirun- Forest Zone).

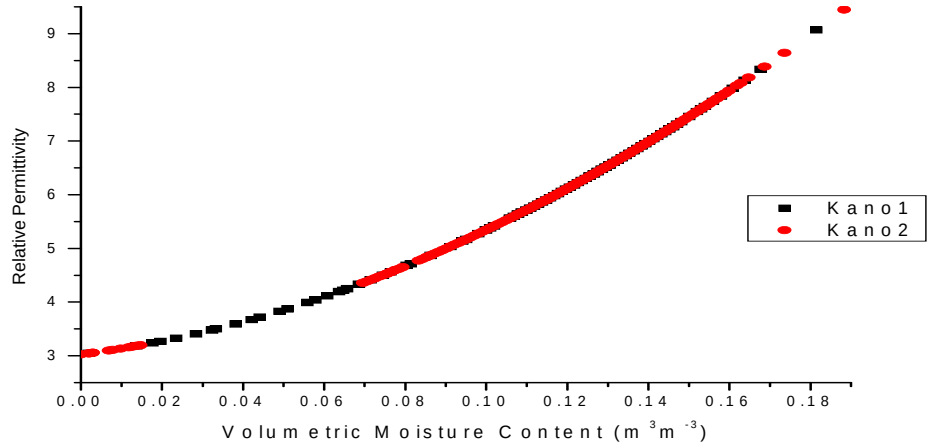


Figure 7. Permittivity against moisture content (Kano- Sudan Savanna Zone).

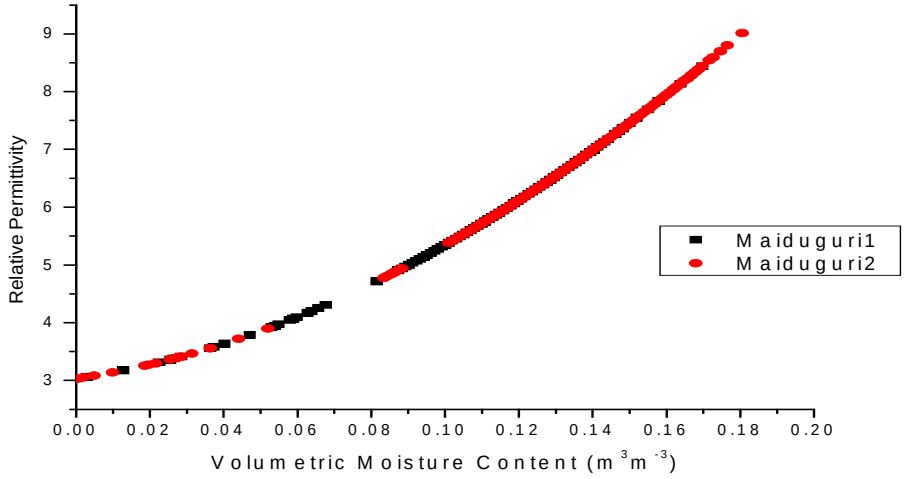


Figure 8. Permittivity against moisture content (Maiduguri-Sahel Savanna Zone).

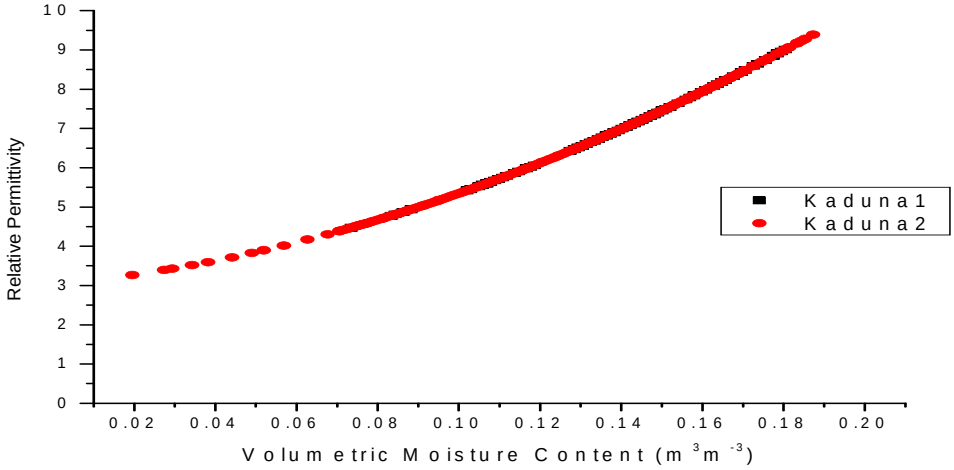


Figure 9. Permittivity against moisture content (Kaduna-Northern Guinea Savanna Zone).

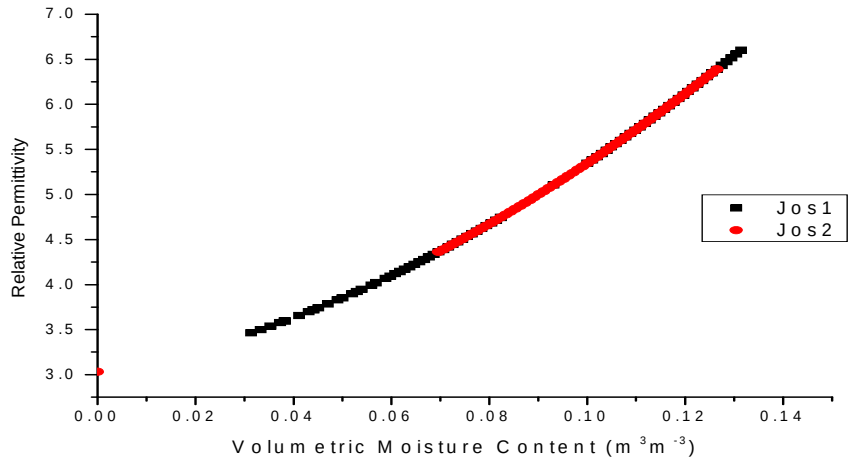


Figure 10. Permittivity against moisture content (Jos-Northern Guinea Savanna Zone).

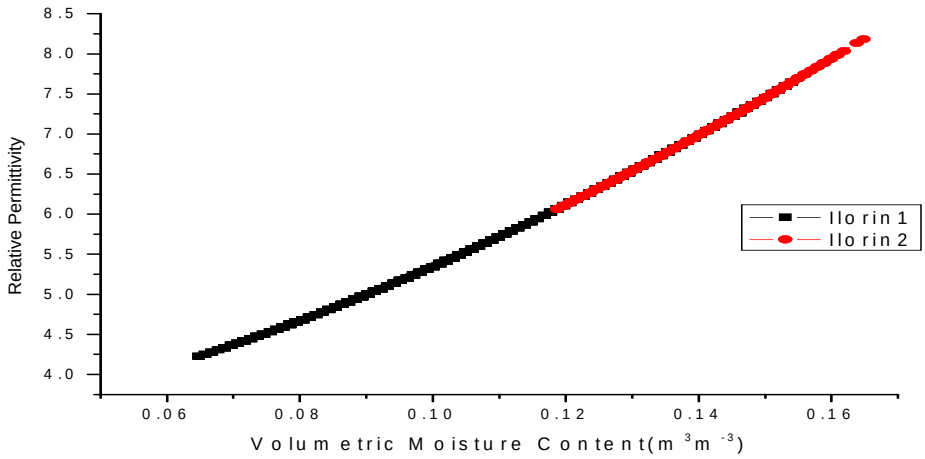


Figure 11. Permittivity against moisture content (Ilorin-Southern Guinea Savanna Zone).

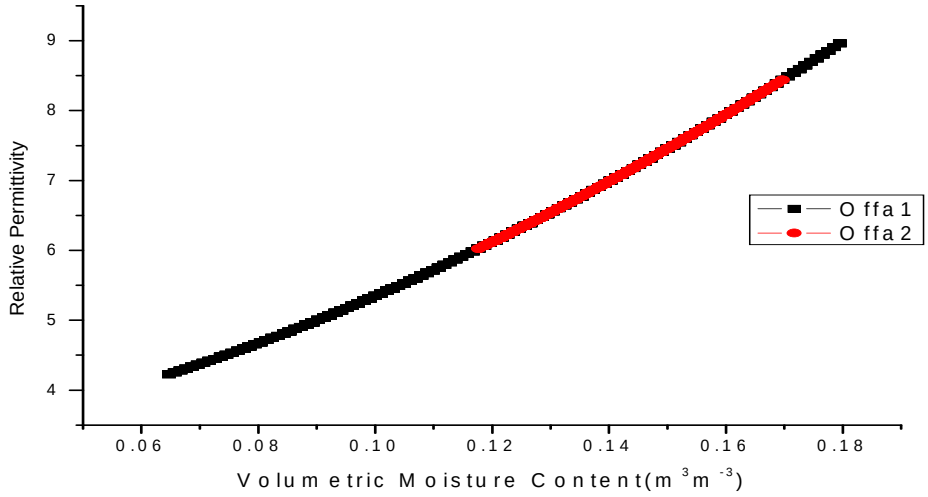


Figure 12. Permittivity against moisture content (Offa-Southern Guinea Savanna Zone).

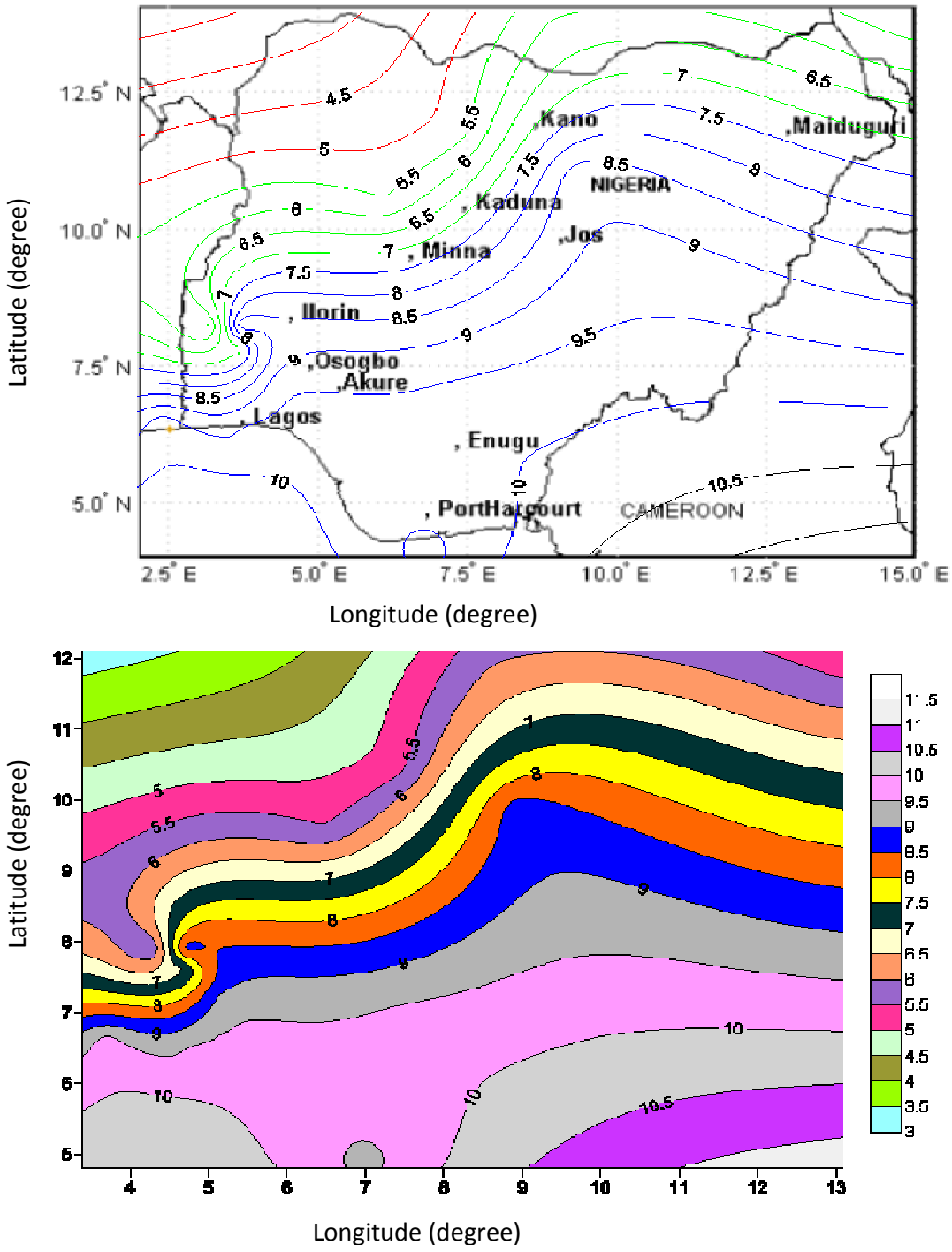


Figure 13. Soil dielectric permittivity contour map of Nigeria.

10.00. This characteristic difference might be due to the fact that Akure receives much more solar radiation throughout the year (Figure 5). These results revealed that permittivity increases with increasing soil moisture contents irrespective of the zone, soil type and geological variation. The results indicate that the main parameter determining permittivity is the volumetric water contents. Having determined the relative dielectric permittivity in relation to volumetric moisture content of the locations investigated, the results were translated into contour maps. With these maps (Figures 13 and 14), it is possible to predict the relative permittivity and moisture content of

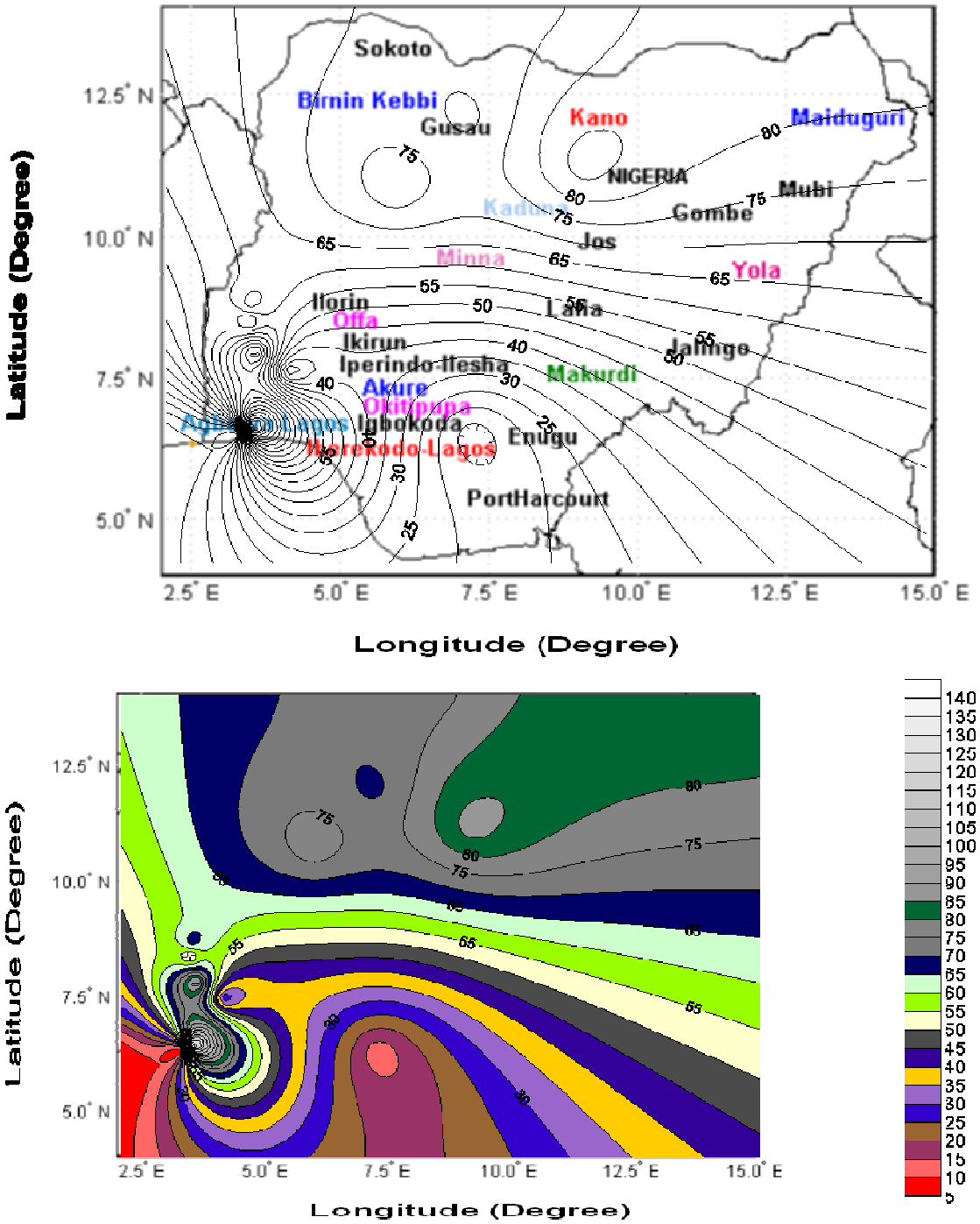


Figure 14. Soil moisture content contour map of Nigeria.

other locations not visited. The results clearly revealed that the forest zone and the coastal swamps zone have the highest permittivity values and this is because these zones receive high intensity of rainfall and hence have higher moisture content.

Using the contour maps aforementioned, it is easy to predict the permittivity values of the locations where the study has not been carried out. The values on the maps correspond to the value of the permittivity in different locations of investigation.

Figure 14 shows soil moisture content contour maps using grid lines and colours. The values on the maps give

the moisture content values obtained in the study. However, the higher the value on the contour lines on the maps, the less the water available in the soil. The results obtained from the contour maps show that soils in the forest and the coastal zones receive more water recharge through rain and ocean as it is evident in the areas with high intensity of contour lines in the coastal and forest area of Nigeria.

Conclusion

An *In-situ* measurement of soil dielectric permittivity had been carried out in this research work using the Vantage Pro 2 dielectric sensors in some selected locations across Nigeria at a fixed frequency of 928 MHz. The types of soil identified in the locations of study are: Sandy clay loam, sandy loam, loamy sand, heavy clay, clay loam and clay. The results show that permittivity increases with increased volumetric water content and that the presence of fine particles with high surface area (for example, clay), cationic species in the pore solution in the soil can lead to increase in soil permittivity. This effect may be due to ionic conduction in various soil types encountered in the course of this work.

The results of this work may be employed as a means of detecting cationic species in the subsurface, in agriculture, radio wave propagation and geotechnics.

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