CHAPTER VII

DIELECTRIC PROPERTIES OF WET AND FERTILIZED SOILS
    AT RADIO AND MICROWAVE FREQUENCIES

7.1 INTRODUCTION:

The complex dielectric spectrum $\varepsilon^* = \varepsilon' - j\varepsilon''$ of geological materials is very much useful in planning ground penetrating radar (GPR) surveys, applications to microwave remote sensing, to understand the behavior of induced-polarization and their use in time domain reflectometry (TDR) measurements. The dielectric constant $\varepsilon'$ is indicative of the material's capability for storing energy in the electric field (electrical polarization) whereas dielectric loss $\varepsilon''$ is indicative of the material's capability for absorbing energy from the alternating electric field. In these materials, energy loss (dissipation) results from conversion of electrical energy to thermal energy (Joule heating) through momentum transfer during collisions as the charge move. The measurement of dielectric properties of soils with moisture content and fertilizer content is also very much useful in agriculture.

Porosity of soil greatly helps to judge the moisture content and moisture movement in the soil. Any operation that reduces aggregation and decreases the amount of organic matter in the soil decreases pore space. Vivek Yadav et al. measured the dielectric properties of fertilized sand for various concentrations of Urea, Shree Ram-33, Shree Ram-50P, D.A.P., and Mosaic at X-band microwave frequency using two-point method. It has been observed that the dielectric constant and dielectric loss of the soil increases with increase in fertilizer content in the soil. Further it has been observed that the dielectric constant increases slowly with increase in D.A.P. content in the soil, where as it increases rapidly with increase in Shree Ram-33 content in the soil. It has been explained that the fertilizer increases the pore space in the soil which is responsible for increase in fertility of the soil.

Shaikh and Navar Khele measured the dielectric properties of black soil with organic and inorganic matters at microwave frequency. It has been observed that the
dielectric constant decreases with increase in frequency, which may be due to molecules having harder time to rotate with increase in frequency. Further it has been observed that the dielectric constant increases linearly with increase in fertilizer content in the soil. It has been explained that according to the theory of electrolyte, in the limit of low concentration, the dependence of dielectric constant is approximately linear. Further it has been explained that with the addition of organic matter in the soil, the water holding capacity of the soil increases. The dielectric loss is found to increase with increase in inorganic and organic matter content in the soil equally. It has been explained that the dielectric loss is associated with ionic conduction.

A capacitive soil moisture sensor having fork like geometry have been designed and used by Eller and Denoth for the field measurements of water content of natural soils in frequency range up to 35 MHz. It estimates complex permittivity of soil for various moisture contents by measuring the impedance with a twin T-bridge. A symmetrical plate condenser of 150 cm$^3$ effective measuring volume was filled with a soil sample and was connected to the feed unit by a coaxial cable with a two-port vector analyzer, in combination with a programmable synthesizer. The amplitude and reflection coefficient of the material under test were measured using the simple T-junction method, to calculate the complex permittivity of MUT.

At frequencies below 5 MHz, even a relatively large sample has dimensions less than the wavelength, and the time of wave propagation remains short in comparison with the wave period. Methods of measuring lumped parameters are known to be used at frequencies up to 100 MHz, provided the dimensions of the sample can still be made substantially less than the wavelength. A parallel plat capacitor with disk electrodes is most commonly used as a sample holder in this frequency range. Levitskaya and Sternberg determined the complex permittivity of the material by measuring the magnitude Z and phase $\phi$ of the sample impedance by using an impedance analyzer. The measurements were carried out in the frequency range from 1 KHz to 100 MHz using disk electrodes, and in the frequency range from 0.1 MHz to 1 GHz using coaxial sample holder.

In reference 5, the lumped parameter approach was used, and the data processing procedure included corrections for stray parameters such as: inductance L, resistance R and capacitance C of the measuring system.
Kandiah and Mitchell measured the dielectric properties of kaolinite clay-water-electrolyte systems in the frequency range from 30 to $10^5$ Hz using a comparator which is essentially a Wheatstone bridge. A cylindrical sample was held between two flat circular platinum electrodes which were platinum black coated. It has been observed that the dielectric increment $(\varepsilon_0 - \varepsilon_m)$ increases with increase in temperature; whereas the characteristic frequency is independent of temperature. Further it has been observed that the larger the hydrated ion size, the larger is the increment and lower characteristic frequency; and that higher the electrolyte concentration the larger is the dielectric increment and the characteristic frequency. Also it is observed that the dispersion of the conductivity and dielectric constant and the characteristic frequency are significantly affected by the ion type and ion concentration.

Sengwa et al. measured the dielectric permittivity of dry and water saturated shale, sandy sandstone and calcareous sandy stone of Jodhpur region at room temperature in the frequency range from 100 Hz to 100 kHz, and also at 10.1 GHz microwave frequency. It has been observed that the dielectric constant of these samples decrease with increase in frequency. Further if has been observed that there is a large enhancement in the $\varepsilon'$ values of water saturated samples in comparison to the $\varepsilon'$ values of the dry samples. The low frequency limiting dielectric constant $\varepsilon_0$, high frequency limiting dielectric constant $\varepsilon_m$, the dielectric relaxation time $\tau$ and distribution parameter $\alpha$ of these samples have been determined by drawing the Cole-Cole plots of these samples. Further ac conductivity of dry and water saturated samples has also been evaluated and reported.

Sengwa and Soni measured the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of dry samples of clay, siliceous earth, fuller's earth, gypsum, lignite, calcite, tourmaline and magnesium rock of opencast mines of western Rajasthan, India, in the frequency range 100 Hz to 100 kHz and also at X-band microwave frequencies. It has been reported that the dielectric constant $\varepsilon'$ decrease with increase in frequency in the lower frequency region. The low frequency limiting dielectric constant $\varepsilon_0$, high frequency limiting dielectric constant $\varepsilon_m$, the dielectric relaxation time $\tau$ and distribution parameter $\alpha$ of these samples were evaluated by drawing the Cole-Cole
plots of these samples. It has been observed that all these minerals have large value of \( \alpha \) and their \( \tau \) values lie in the range from 0.1 to 11 ms. Calculated values of frequency dependent ac conductivity have shown a linear behavior between \( \log \sigma \) and \( \log f \).

The dielectric properties of moist soil and fertilized soil have been measured in the frequency range 10 kHz to 2 MHz. The following sections describe sample preparation, experimental set up and measurement technique. The result of the study has also been presented here.

7.2 SAMPLE PREPARATION:

The wet soil samples of Gandhinagar district sandy loam soil for various moisture contents were prepared in the laboratory by adding various proportions of double distilled water in the dry soil, and the measurements for the estimation of dielectric properties of wet soil samples were carried out using the precision LCR meter.

The addition of fertilizer in the soil increases the water holding capacity of the soil\(^3\). To observe the effect of fertilizer on the soil we selected two fertilizers (i) Sulphet of Potash (SOP) also called Potassium Sulphet, and (ii) Zinc Chelate. The SOP contains potash (as K\text{2O}) percent by weight minimum- 50.0, Sulpher (as S) percent by weight minimum- 17.5. SOP is imported in India from Finland. It is prescribed to prepare 0.2% to 0.5% solution of SOP (by desolving 200 to 500 gm / 100 liters of water). It is 100% water soluble fertilizer for foliar spray. It is recommended for use on Cotton and Vegetables. The microgranual formulation of Zinc Chelate contains water soluble Zinc (Zn) minimum = 12.0 %, Zinc (Zn) Chelated by EDTA minimum = 12.0 %, and pH stability range was 4.9 in aqueous solution. It is recommended for use on Paddy, Cotton, Chillies, Vegetables, Sugarcane, Groundnut, and Horticultular crops. It has been prescribed to dissolve 100-150 gm of Librel Zinc Chelate in 150-200 Ltrs. of water and to be sprayed over one acre of standing crop or if required the dose can be increased. Zinc Chelate fertilizer is manufactured by Ciba UK Plc, Bradford, West Yorkshire, UK.
Further the dry soil samples of Palanpur district sand and Gandhinagar district sandy loam soil were taken. Adding some fixed proportion of fertilizers Sulphet of Potash (SOP) and Zinc Chelate in the double distilled water, various solutions in % of fertilizer in water were prepared. 6 ml of these solutions were added in the soil samples of 100 gm weight and mixed well. The % solutions of fertilizers by weight in the soil samples are shown in the table (7.1). The volumetric moisture content in the soil samples for the fertilized water solutions was calculated as explained in chapter V (5.2.1).

The dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of these fertilized soil samples were also measured at spot frequencies of 0.5 GHz, 1.0 GHz and 1.5 GHz, using Vector Network Analyzer employing the method as described in chapter IV (4.2.2).
Table (7.1): % solution content of fertilizer in the soil samples:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Weight of soil (gm)</th>
<th>Fertilizer Type</th>
<th>Weight of Fertilizer in 50 ml double distilled water</th>
<th>% solution of fertilizer</th>
<th>Volume of fertilized water</th>
<th>Volumetric moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gandhinagar district</td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>11 mg</td>
<td>0.22 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>16 mg</td>
<td>0.32 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>20 mg</td>
<td>0.40 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>25 mg</td>
<td>0.50 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td>Gandhinagar district</td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>40 mg</td>
<td>0.08 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>60 mg</td>
<td>0.12 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>80 mg</td>
<td>0.16 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>100 mg</td>
<td>0.20 %</td>
<td>6 ml</td>
<td>0.083</td>
</tr>
<tr>
<td>Palanpur district</td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>120 mg</td>
<td>0.24 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td>Sand</td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>170 mg</td>
<td>0.34 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>250 mg</td>
<td>0.50 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Sulphate of Potash (SOP)</td>
<td>310 mg</td>
<td>0.62 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td>Palanpur district</td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>40 mg</td>
<td>0.08 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td>Sand</td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>50 mg</td>
<td>0.10 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>60 mg</td>
<td>0.12 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>Zinc Chelate (Librel)</td>
<td>90 mg</td>
<td>0.18 %</td>
<td>6 ml</td>
<td>0.0954</td>
</tr>
</tbody>
</table>
7.3 EXPERIMENTAL SET UP:

A precision LCR meter Agilent make E-4980A operating in the frequency range from 20 Hz to 2 MHz was used for the measurements of capacitance and resistance offered by the coaxial capacitor. The LCR meter can take simultaneous measurements during one trigger in the frequency range from 20 Hz to 2 MHz in 201 linear steps (or logarithmic steps if required).

A standard four point probe Agilent 16089A with Kelvin clip leads was connected to the LCR meter. The coaxial capacitor was connected at the end of the probe and fixed in a stand pointing downward.

The compensation of the LCR meter and coaxial capacitor was done in following steps:

(i) Open: The LCR meter was compensated for open circuit coaxial capacitor with air as dielectric medium.

(ii) Short: A vessel containing mercury was raised from the lower side of the capacitor till it fills the capacitor completely and then LCR meter was compensated for short.

The LCR meter is said to be compensated up to the end of the coaxial capacitor.

7.4 STANDARDIZATION OF CAPACITOR:

The coaxial capacitor was standardized using the liquids of known dielectric constant, as follows:

(1) The capacitance \( C_0 \) and resistance \( R_0 \) of the coaxial capacitor were measured using LCR meter for open circuit condition with air as dielectric for the frequency ranging from 20 Hz to 2 MHz.

(2) Now a small vessel containing CCl\(_4\) (AR grade) was kept below the coaxial capacitor. Then raising the vessel until the CCl\(_4\) level completely fills the capacitor, the capacitance \( C_P \) and resistance \( R_P \) were measured for the frequency ranging from 20 Hz to 2 MHz.

(3) CCl\(_4\) was removed from the coaxial capacitor. Then a vessel containing Acetone was raised below the capacitor so that it fills the capacitor
completely. Now Acetone was removed and time was allowed for the Acetone to evaporate completely. Again the capacitance and resistance of the empty capacitor were measured to verify the initial values of the empty capacitor as explained in step (1).

(4) Now the steps (2) and (3) were repeated for other standard liquids of known dielectric constant like Benzene and Chloro-benzene.

For each capacitance value of standard liquid, the difference capacitance $C_p - C_0$ was calculated. A graph was drawn for the dielectric constant against $C_p - C_0$ for the known standard liquids, as shown in figure (7.1).

![Graph](image)

Figure (7.1). A graph of the dielectric constant $\varepsilon'$ plotted against $C_p - C_0$ in pF.

The equation for the straight trend line connecting all points was obtained from the graph as

$$y = 2.0139 x + 0.98 \quad \ldots \ldots (1)$$

where, $x = C_p - C_0$ in pF,

$y = $ Dielectric constant $\varepsilon'$,

2.0139 = slope of the straight line from the graph of figure (7.1), and

0.98 = intercept of the straight line from the graph of figure (7.1).
The correlation coefficient of difference capacitance values and the dielectric constant for the linear trend line was observed to be 0.9999.

The dielectric constant for each sample was calculated using the equation

$$\varepsilon'_{\text{meas}} = 2.0139 \, (C_p - C_0) + 0.98 \quad \text{.....(2)}$$

The dielectric loss of the sample (liquid or soil) for each frequency was calculated using equation

$$\varepsilon'' = \varepsilon' \tan \delta \quad \text{.....(3)}$$

Where

$$\tan \delta = \frac{\varepsilon'}{\omega \varepsilon' \varepsilon_0} \quad \text{.....(4)}$$

For the coaxial capacitor the conductivity and dielectric constant are

$$\sigma' = \frac{\ln(b/a)G}{2\pi H} = \frac{\ln(b/a)}{2\pi f R}, \quad \varepsilon' = \frac{\ln(b/a)C}{2\pi f \varepsilon_0} \quad \text{.....(5)}$$

Substituting results (4) and (5) in (3), we get

$$\varepsilon'' = \varepsilon' \tan \delta = \frac{\sigma'}{\omega \varepsilon_0} = \frac{\ln(b/a)}{2\pi f HR \omega \varepsilon_0} = \frac{\varepsilon'_{\text{meas}}}{C \rho \omega} \quad \text{.....(6)}$$

In equation (6),

- $\varepsilon'$ = measured value of dielectric constant from equation (2).
- $a$ = radius of inner cylinder
- $b$ = radius of outer cylinder
- $f$ = frequency of measurement,
- $H$ = length (height) of the capacitor
- $R_p$ = resistance measured using LCR meter at each frequency,
- $C_p$ = capacitance of coaxial capacitor with soil sample, at each frequency,
\[ C_0 = \text{capacitance of empty (air filled) coaxial capacitor, at each frequency.} \]

In the actual calculation we considered \( C = C_p - C_0 \) and \( R = R_p \) as explained in equation (2).

The conductivity \( \sigma' \) of the soil samples for all frequencies of measurements was calculated using the equation

\[
\sigma' = \omega \varepsilon'' \varepsilon_0 \quad \text{......(7)}
\]

A graph of \( \sigma' \) against frequency was drawn for each soil sample. Extending the linear fitting line towards lower frequency end, the value of intercept of \( \sigma' \) for zero frequency was obtained, called dc conductivity \( \sigma' \, \text{dc} \). The value of dielectric loss \( \varepsilon'' \) due to dc conductivity was calculated at each frequency using the equation

\[
\varepsilon'' \, \text{dc} = \frac{\sigma' \, \text{dc}}{\omega \varepsilon_0} \quad \text{......(8)}
\]

Hence subtracting the dc conductivity loss \( \varepsilon'' \, \text{dc} \) from the measured value of dielectric loss \( \varepsilon'' \) from the equation (44), we get the actual dielectric loss \( \varepsilon'' \, \text{actual} \) as

\[
\varepsilon'' \, \text{actual} = \varepsilon'' - \frac{\sigma'}{\omega \varepsilon_0} \quad \text{......(9)}
\]

The measurements were carried out for the other liquids like 1-Propanol and Acetone (AR Grade) as explained in steps (2) and (3) in measurement procedure. Again subtracting the capacitance of air filled capacitor from the measured values of the capacitor filled with 1-Propanol and Acetone. Substituting the respective values in equation (2), we get the dielectric constant of 1-Propanol and Acetone. The calculated values are compared with the known standard values given in the literature as shown in the table (3), and are in good agreement with literature values with error less than 3%.

Table (7.2) shows the comparison of the measured values with the values obtained from literature. The results are in very good agreement with the literature values.
Table (7.2): Comparison of measured values and literature values of dielectric constant.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon_0$ known at given temperature</th>
<th>$\varepsilon'$ measured at 2 MHz</th>
<th>$\Delta \varepsilon' / \varepsilon'$ in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0.98</td>
<td>2 %</td>
</tr>
<tr>
<td>CCl₄</td>
<td>2.238 $^{11}$ (20° C)</td>
<td>2.225</td>
<td>0.581 %</td>
</tr>
<tr>
<td>Benzene</td>
<td>2.2836 $^{11}$ (20° C)</td>
<td>2.294</td>
<td>-0.455 %</td>
</tr>
<tr>
<td>Chloro-benzene</td>
<td>5.708 $^{11}$ (20° C)</td>
<td>5.491</td>
<td>0.396 %</td>
</tr>
<tr>
<td>1-Propanol</td>
<td>19.5 $^{11}$ (20° C)</td>
<td>19.253</td>
<td>1.267 %</td>
</tr>
<tr>
<td>Acetone</td>
<td>20.7 $^{11}$ (25° C)</td>
<td>20.630</td>
<td>0.338 %</td>
</tr>
</tbody>
</table>

A vessel containing wet soil sample of Gandhinagar district sandy loam soil was raised up slowly taking care that the position of the capacitor does not change, and slowly knocking the vessel it was raised till the coaxial capacitor was completely filled with the wet soil (the air in empty part came out through vertical groves). Now the capacitance $C_P$ and resistance $R_P$ of the soil filled capacitor were measured using the LCR meter for the whole range of the frequency. Subtracting the capacitance of empty air filled capacitor from the capacitance of the soil filled capacitor; the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the Gandhinagar district soil were calculated using equations (40) and (47).

The measurements were carried out for the estimation of dielectric constant, dielectric loss, and loss tangent of Gandhinagar district sandy loam soil, for various moisture contents and frequency variation from 10 kHz to 2 MHz using the LCR meter. The dc conductivity of the soil for all moisture contents was also calculated using the method explained by Sengwa et al. The value of dielectric loss is obtained by subtracting the dc conductivity from the measured value of dielectric loss.

The measurements for fertilized wet soil samples of Gandhinagar district sandy loam soil and Palanpur district sand were also carried out.
7.5 RESULTS AND DISCUSSION:

It can be observed from figure (7.2) that the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the (Gandhinagar district sandy loam) wet soil decreases with increase in frequency from 10 kHz to 2 MHz. Similar results have been reported in literature \(^1,4,8\). The decrease in $\varepsilon'$ with increase in frequency range from 100 Hz to 100 kHz is the common characteristic of the geological materials \(^1\). Further it is observed that in this frequency range the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the soil increases vary rapidly with increase in moisture content in the soil. A very large enhancement in the values of $\varepsilon'$ and $\varepsilon''$ is observed at lower frequency with increase in moisture content in the soil. This very large enhancement in the permittivity value of wet soil may be due to electro chemical polarization \(^1\) which arises due to increase in surface charge carrier density in presence of water molecules in the pore spaces of the soil.

The variation of the measured dielectric constant $\varepsilon'$ (eps'), dielectric loss $\varepsilon''$ (eps''), and corrected dielectric loss $\varepsilon''$ (actual eps'') after subtracting the contribution of ohmic (dc) conductivity contribution is shown in figure (7.3) for $W_v = 0.219$ cm$^3$/cm$^3$. It can be observed that the ohmic (dc) conductivity contribution to the dielectric loss in wet soil is more at lower frequency end.

The variation of loss tan $\delta$ of the Gandhinagar district sandy loam soil for various moisture contents in the frequency range from 10 kHz to 2 MHz is shown in figure (7.4). It is observed that at very low moisture content of $W_v = 0.005$ cm$^3$/cm$^3$, a very small peak is observed at 1.262 MHz (tan $\delta = 0.37$). As moisture content in the soil increases the value of tan $\delta$ increases (tan $\delta = 7.88$ at 238 kHz for $W_v = 0.097$ cm$^3$/cm$^3$; tan $\delta = 12.95$ at 160 kHz for $W_v = 0.178$ cm$^3$/cm$^3$; and tan $\delta = 19.99$ at 150 kHz for $W_v = 0.219$ cm$^3$/cm$^3$), which also show shift of tan $\delta$ towards lower frequency side as moisture content in the soil increases. Analogous behavior has been reported in literature \(^10\). The shifting of loss peak towards lower frequency with increase in moisture content in the soil suggests the change in size of the orienting ions in the presence of pore water in the samples \(^10\).
Figure (7.5) shows the variation of real and imaginary values of conductivity with variation in frequency for various moisture contents in the Gandhinagar district sandy loam soil. It can be observed from figure (7.5-a) that for dryer soil (Wv = 0.005 cm³/cm³) the frequency dependent real part of conductivity $\sigma'$ of the soil is very small at lower frequency ($\sigma' \sim 1.74 \times 10^{-6}$ at 10 kHz) and increases with increase in frequency ($\sigma' \sim 1.6 \times 10^{-4}$ at 2 MHz). At higher moisture contents in the soil $\sigma'$ increases slowly with increase in frequency. Analogous behaviour was observed by Sternberg and Levitskaya, Sangwa et al., and Sangwa and Soni. The increase in the value of conductivity $\sigma'$ of wet soil samples shows that the conductivity of soil-water matrix increases with increase in moisture content in the soil. The imaginary conductivity $\sigma''$ of the dryer soil (Wv = 0.005 cm³/cm³) is very small at lower frequency ($\sigma'' \sim 5 \times 10^{-6}$ at 10 kHz) and increases with increase in frequency ($\sigma'' \sim 0.00045$ at 2 MHz). At given higher moisture content in the soil the conductivity $\sigma''$ decreases with increase in frequency up to certain minimum value after which it increases with increase in frequency. It has been observed that the minimum value of $\sigma''$ shifts towards lower frequency end as moisture content in the soil increases ($\sigma'' \sim 0.0014$ at 178.25 kHz for Wv = 0.097 cm³/cm³; $\sigma'' \sim 0.00187$ at 158.865 kHz for Wv = 0.178 cm³/cm³; $\sigma'' \sim 0.0021$ at 149.987 kHz for Wv = 0.219 cm³/cm³). Further it has been observed that the value of $\sigma''_{minimum}$ increases with increase in moisture content in the soil.

Figure (7.6) shows the variation of dc (ohmic) conductivity with moisture content in the sandy loam soil of Gandhinagar district. It has been observed that for dryer soil (Wv = 0.005 cm³/cm³) the dc conductivity is of the order of $4 \times 10^{-7}$, whereas for wet soil it increases with increase in moisture content in the soil approaching saturation value of 0.0214 at (Wv = 0.219 cm³/cm³) for the given soil sample.

Figure (7.7) shows the variation of dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the wet fertilized soils (Sandy loam soil of Gandhinagar district, and Sandy soil of Palanpur district) for various concentrations of different fertilizers [Sulphate of Potash (SOP), and Zinc Chelate] in the frequency range from 10 kHz to 2 MHz. It has been observed that the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the wet fertilized soils decrease with increase in frequency from 10 kHz to 2 MHz. The dielectric
constant $\varepsilon'$ and dielectric loss $\varepsilon''$ increases with increase in % concentration of fertilizer content in the wet soil. This behavior is mainly dependent on the moisture content in the soil. There is approximately linear increasing the $\varepsilon'$ with percentage volume of organic and inorganic metal. This may be due to the fact that the added organic and inorganic matter forms a chemical composition of low concentration along with the chemicals present in the soil. According to the theory of Electrolyte, in the limit of low concentration the dependence of $\varepsilon'$ is approximately linear \(^3\). By adding fertilizer the water holding capacity of soil improves. The dielectric permittivity of soil directly depends on the amount of moisture content present in the soil. The higher moisture content increases the dielectric constant of the soil.

The dielectric loss $\varepsilon''$ of soil increases with increase in % volume of fertilizer. The reason may be that $\varepsilon''$ is a parameter which describes the motion of electric charge i.e. is a conduction phenomenon \(^3\). Certain dielectrics display conduction which arises from the actual charge transport (ionic conduction in electrolytes) rather than due to the displacement current. Such conduction is described by volume conductivity which adds an additional term to the dielectric loss $\varepsilon''$. Due to this additional term the dielectric loss increases with increase in fertilizer content in the soil.

Figure (7.8) shows the variation of dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the soils (Sandy loam soil of Gandhinagar district, and Sandy soil of Palanpur district) for various % concentrations of fertilizers [Sulphet of Potash (SOP), and Zinc Chelate] at spot frequency of 2 MHz. It can be observed that the dielectric constant of the soils increases slowly with increase in % concentration of fertilizers SOP and Zinc Chelate. The dielectric loss increases rapidly with increase in % concentration of fertilizers in the soils.

Figure (7.8-a) shows the variation of dielectric constant and dielectric loss of Gandhinagar district sandy loam soil for various % concentrations of Sulphet of Potash (SOP) in the soil at 2 MHz. It can be observed that for the variation of fertilizer SOP from 0.22% to 0.50% in the soil the dielectric constant $\varepsilon'$ increases from 6.12 to 8.99 and dielectric loss $\varepsilon''$ increases from 60.4 to 90.4. Figure (7.8-b) represents the variation of dielectric constant and dielectric loss of Gandhinagar district sandy loam soil for various % concentrations of Zinc Chelate in the soil at 2 MHz. It can be observed that for the variation of fertilizer Zinc Chelate from 0.08% to
0.20% in the soil the dielectric constant $\varepsilon'$ increases from 9.99 to 12.64 and dielectric loss $\varepsilon''$ increases from 82 to 134.5. The variation of dielectric constant and dielectric loss of Palanpur district sandy soil for various % concentrations of Sulphet of Potash (SOP) in the soil at 2 MHz is shown in figure (7.8-c). It can be observed that for the variation of fertilizer SOP from 0.24% to 0.62% in the soil the dielectric constant $\varepsilon'$ increases from 8.12 to 11.25 and dielectric loss $\varepsilon''$ increases from 68.9 to 115.4.

Further the variation of dielectric constant and dielectric loss of Palanpur district sandy soil for various % concentrations of Zinc Chelate in the soil at 2 MHz is represented in figure (7.8-d). It can be observed that for the variation of fertilizer Zinc Chelate from 0.08% to 0.18% in the soil the dielectric constant $\varepsilon'$ increases from 8.10 to 9.94 and dielectric loss $\varepsilon''$ increases from 63.2 to 98.65. The reason for large increase in $\varepsilon''$ may be due to the fact that $\varepsilon''$ describes the motion of electric charge i.e. is a conduction phenomenon, which arises from the actual charge transport (ionic conduction in electrolytes), described by volume conductivity that adds an additional term to the dielectric loss $\varepsilon''$.

Figure (7.9) shows the variation of loss tan $\delta$ of the wet fertilized soils for various concentrations of different fertilizers in the frequency range from 10 kHz to 2 MHz. It has been observed that a loss peak appears near $10^5$ Hz for the wet soils for all the % concentrations of fertilizers in the soils. The loss peak is observed to shift towards lower frequency end with increase in fertilizer content in the soils except that of SOP in Palanpur district sandy soil in which the loss peak is observed to shift towards higher frequency end, the reason for this behavior is yet to be found by taking more observations on different types of soils.

The variation of real and imaginary conductivity of the wet fertilized soils (Sandy loam soil of Gandhinagar district, and Sandy soil of Palanpur district) for various concentrations of different fertilizers [Sulphet of Potash (SOP), and Zinc Chelate] in the frequency range from 10 kHz to 2 MHz is shown in figure (7.10). It has been observed that the real conductivity $\sigma'$ of the soils increase slowly with increase in frequency. The real conductivity $\sigma'$ of the soils also increase with increase in % concentration of fertilizer in the soil. The imaginary conductivity $\sigma''$ of the soils decrease with increase in frequency up to certain value of $\sigma''_{\text{minimum}}$ after which it
increases with increase in frequency. The value of $\sigma''_{\text{min}}$ is observed to shift towards higher frequency end with increase in % concentration of fertilizer in the soils except that for SOP in Gandhinagar district sandy loam soil in which the value of $\sigma''_{\text{min}}$ is observed to shift towards lower frequency end with increase in % concentration of SOP in the soil.

Figure (7.11) shows the variation of dc conductivity of the wet fertilized soils for various concentrations of fertilizers. It has been observed from figure (7.11-a) that the dc conductivity of Gandhinagar district sandy loam soil increases from $\sigma_{dc} = 0.0035$ to 0.0057 for % solution variation of SOP from 0.22% to 0.50%. Figure (7.11-b) shows that the dc conductivity of Gandhinagar district sandy loam soil increases from $\sigma_{dc} = 0.0052$ to 0.009 for % solution variation of Zinc Chelate from 0.08% to 0.20%. Further it can be observed from figure (7.11-c) that the dc conductivity of Palanpur district sandy soil increases from $\sigma_{dc} = 0.0045$ to 0.0099 for % solution variation of SOP from 0.24% to 0.62%. Figure (7.11-d) shows the variation of dc conductivity of Palanpur district sandy soil from $\sigma_{dc} = 0.0034$ to 0.0067 for % solution variation of Zinc Chelate from 0.08% to 0.18%. Thus it can be concluded that Zinc Chelate increases the dc conductivity of the soil more rapidly in comparison with SOP.

The variation of dielectric constant and dielectric loss of the wet fertilized soils for various concentrations of different fertilizers at spot frequencies of 0.5 GHz, 1.0 GHz and 1.5 GHz measured using Vector Network Analyzer (method of measurement described in chapter IV) is shown in figure (7.12). It has been observed that at given fertilizer content in the soil the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the soils decrease with increase in frequency from 0.5 GHz to 1.5 GHz. Further it is observed that at given frequency of measurement the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the soils increase with increase in fertilizer content in the soil. Further it is observed that the values of the dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ of the soils for the frequency band from 0.5 GHz to 1.5 GHz are very small in comparison with those obtained for the lower (radio) frequency band from 10 kHz to 2 MHz. At 2 MHz for the variation of fertilizer SOP from 0.24% to 0.62% in the soil the dielectric constant $\varepsilon'$ increases from 8.12 to 11.25 and dielectric loss $\varepsilon''$ increases from 68.9 to 115.4; whereas at 1.0 GHz for the variation of fertilizer SOP from 0.24% to 0.62% in
the soil the dielectric constant $\varepsilon'$ increases from 4.47 to 4.94 and dielectric loss $\varepsilon''$ increases from 0.58 to 0.72. This shows that for given variation of fertilizer in the soil the variation of dielectric constant and dielectric loss values is more for lower (radio) frequencies (e.g. at 2 MHz), rather than that for the microwave frequencies form 0.5 GHz to 1.5 GHz.
Figure 7.2: The measured values of dielectric constant and dielectric loss of Gandhinagar district wet sandy loam soil for various moisture contents in the frequency range from 10 kHz to 2 MHz.
Figure 7.3: The measured values of dielectric constant, dielectric loss, and actual dielectric loss after subtracting dc conductivity dependent dielectric loss of Gandhinagar district wet sandy loam soil at $W_v = 0.219$ in the frequency range from 10 kHz to 2 MHz.

Figure 7.4: The calculated values of loss $\tan \delta$ of Gandhinagar district wet sandy loam soil for various moisture contents in the frequency range from 10 kHz to 2 MHz.
Figure 7.5: The real and imaginary values of conductivity for variation of frequency from 10 kHz to 2 MHz, for various moisture contents in the soil.

Figure 7.5-a

Figure 7.5-b
Figure 7.6: DC conductivity for various moisture contents (cm$^3$/cm$^3$) in the soil.

\[ y = -3.4514x^3 + 1.0526x^2 - 0.0084x + 2E-05 \]

\[ R^2 = 1 \]
Figure 7.7: The variation of dielectric constant and dielectric loss of the wet fertilized soils for various concentrations of different fertilizers.

Figure 7.7-a

Figure 7.7-b
Figure 7.7-c

Gandhinagar sandy loam + Zinc Chelate

- Soil + 0.08 % Solution
- Soil + 0.12 % Solution
- Soil + 0.16 % Solution
- Soil + 0.20 % Solution

Figure 7.7-d

Gandhinagar sandy loam + Zinc Chelate

- Soil + 0.08 % Solution
- Soil + 0.12 % Solution
- Soil + 0.16 % Solution
- Soil + 0.20 % Solution
Figure 7.7-e

Figure 7.7-f
Figure 7.7-g

Figure 7.7-h
Figure 7.8: The variation of dielectric constant and dielectric loss of the wet fertilized soils for various concentrations of different fertilizers at spot frequency of 2 MHz.

Figure 7.8-a

Figure 7.8-b
Figure 7.8-c

Figure 7.8-d
Figure 7.9: The variation of loss tan δ of the wet fertilized soils for various concentrations of different fertilizers in the frequency range from 10 kHz to 2 MHz.

![Graph](image)

Figure 7.9-a

![Graph](image)

Figure 7.9-b
Figure 7.9-c

Figure 7.9-d
Figure 7.10: The variation of real and imaginary conductivity of the wet fertilized soils for various concentrations of different fertilizers in the frequency range from 10 kHz to 2 MHz.

**Figure 7.10-a**

**Figure 7.10-b**
Figure 7.10-c

Figure 7.10-d
Figure 7.10-e

Figure 7.10-f
Figure 7.10-g

Figure 7.10-h
Figure 7.11: The variation of dc conductivity of the wet fertilized soils for various concentrations of different fertilizers.

![Graph](image)

**Figure 7.11-a**

![Graph](image)

**Figure 7.11-b**
Figure 7.11-c

Figure 7.11-d
Figure 7.12: The variation of dielectric constant and dielectric loss of the wet fertilized soils for various concentrations of different fertilizers at spot frequencies of 0.5 GHz, 1.0 GHz and 1.5 GHz measured using VNA.

Figure 7.12-a

Figure 7.12-b
Figure 7.12-c

Figure 7.12-d
Figure 7.12-e

Figure 7.12-f
Figure 7.12-g

Figure 7.12-h
REFERENCES:


