THE MEASUREMENT OF THE DIELECTRIC CONSTANT OF UNDERGROUND CLAY PIPES

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Abstract

Many of the Underground utilities in the United States are in need of rehabilitation. It is then necessary to find ways to improve and measure intrastructural characteristics. An advanced ultra-wideband (UWB) based radar was developed at Louisiana Tech University to assess the intrastructure of underground pipes. A significant contribution in the process of designing such an ultra-wideband (UWB) based radar system came from a two- and three-dimensional numerical modeling of the propagation of electromagnetic pulses inside and outside buried non-metallic pipes using the finite difference time domain (FDTD) technique. The electrical properties of the materials involved in exhibit show a significant variation as a result of the moisture content, mineral content, bulk density, temperature and frequency of the electromagnetic signal propagating through it. In this paper, the dielectric constant of clay pipe are measured over a microwave frequency range from 1 Ghz to 18 Ghz including the effects of moisture and chloride content. The change in the dielectric constant of clay pipe becomes significant as the moisture level increases. A high performance software package called MU-EPSLNTM was used for the calculations.

Keywords*: dielectric constant, underground clay pipe, and finite difference time domain technique.*

Introduction

Of the approximately 11 million miles of underground utilities in the U.S. potable, storm and wastewater distribution and collection systems make up around 6 million miles. Efficient operation of such a systems is essential in maintaining basic societal needs. Some examples include public health and environmental protection. Still, underground utilities are suffering from increasing rates of failure. Report released by Battelle Memorial Institute [1] estimated annual expenditures on underground rehabilitation in the U.S. at 6 billion dollars, with an annual projected grow of 9% to 11%.

It is then necessary to find ways to improve and measure infrastructural characteristics. An advanced ultra-wideband (UWB) based radar was developed at Louisiana Tech University to assess the intrastructure of underground pipes. A significant contribution in the process of designing such an ultra-wideband (UWB) based radar system came from a two- and three-dimensional numerical modeling of the propagation of electromagnetic pulses inside and outside buried non-metallic pipes using the finite difference time domain (FDTD) technique [3]. To satisfy the Federal Communication Commission (FCC) imposed limits on the electromagnetic emissions for UWB imaging systems the condition assessment radar was designed at Louisiana Tech University to operate in the bandwidth of 3.1 to 10.6 GHz.

Some of the important electrical properties of the materials are the moisture content, mineral content, bulk density, temperature and frequency of the electromagnetic signal propagating through it. The measurement of the complex dielectric is important in many areas of

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research. Dielectric measurements are important in this research, because it can provide the electric or magnetic characteristics of materials. There is a growing industrial demand for dielectric characterization of materials for design, manufacturing, and quality control purposes in industries [4]. This research measures the dielectric properties of materials using a coaxial line fixture. A method for determining the dielectric constant of clay and clay pipe will be described in this research. A high performance software package called MU-EPSLN^{TM} has been used to do the calculations. The MU-EPSLN^{TM} is a complete software package for making S-parameter measurements using one and two port coax or waveguide fixtures. Data reduction routines to calculate the complex permeability and permittivity of materials as well as other parameters are provided. The user has access to all raw and processed data, so that it can be studied at any time. The user can select bands to be swept; many frequencies can be swept depending on the VNA. All the capabilities of the VNA are available to the user either through the external controller or the front panel [5]. The complex μ and ϵ are normalized relative to free space parameters $μ_0$ and $ϵ_0$.

The complex μ and ϵ are written as eq. (1) and eq. (2).

$$μ = μ' - i\,μ''$$ (1)

$$ϵ = ϵ' - i\,ϵ''$$ (2)

where μ'' and ϵ'' are nonnegative real numbers and i = $\sqrt{-1}$. The complex time dependence in the relevant field equations is of the form $e^{jωt}$. The MU-EPSLN^{TM} program calculates the free space and short backed reflection and transmission coefficients for a material. The sample thickness is input by the user. This implementation is based upon a direct analogy of TEM propagation in a coaxial line, and a normally incident plane wave propagation in a coaxial line, and a normally incident plane wave propagating in free space [6]. A measurement that uses the Transmission/Reflection line technique involves putting a sample in a section of a coaxial line, and measuring the two ports complex scattering parameters with a vector network analyzer (VNA). The VNA must be calibrated before a measurement can be made.

For good dielectric measurement, a high electric field is required. This measurement technique allows for the measurement of permittivity and permeability of the dielectric material. The VNA can be calibrated and the samples are then placed in the sample holder. The better that the sample fits the less the measurement uncertainty will be. The measurement accuracy is limited by the numerical uncertainty and by the air gaps [7]. Cylindrical samples specimens were made using a drill press. The specimens were drilled from clay and clay pipe. Dimensions of the specimens varied from two to three cm in diameter to four to five cm in height.

A number of different conditions of the specimens were used for the measurements: (1) saturated specimens with moisture on the inside for one month or more, (2) air dried specimens exposed to just room temperature and humidity, and finally (3) specimens were placed into saltwater for one month or more. Clay is a dielectric, nonmagnetic material. Dielectric materials are usually made up of atoms whose valence electron shells are nearly full, resulting in low conductivity. Using a coaxial transmission line, a particular material's dielectric properties can be tested as amounts of certain substances within it are varied [8].

The early design of early sewers was a major problem because there were no standard for underground clay pipes. In 1903, the ASTM started recommending standards for clay sewer pipes. These new standards were the first in this industry. Underground Clay pipes are generally placed in one of two classifications: rigid or flexible [9].

Clay pipes are generally considered examples of a rigid pipe. Underground clay pipes are produced from the raw materials like clay, grog (chamotte) and water. These clay pipes have exceptional properties with respect to chemical resistance, mechanical strength, impermeability, and hardness [10].

Underground Clay Pipes are a maded of naturally occurring material. It typically forms due to the weathering of feldspar. One of the major clay minerals is kaolinite. There are approximately 30 different types of clays, but most natural clays are mixtures of these different types, along with other weathered minerals [11-13]. Clay pipes are a mixture of different clay minerals, which makes it a multi-phased heterogeneous material. Dielectric constant is a measure of the polarizability of a material. Polarization is the spatial separation of charges due to an applied electric field. The mechanisms that cause polarization depend on the frequency of the applied electric field and the composition of the material. Single phase, homogeneous materials experience only high frequency polarization mechanisms: electronic, ionic, and molecular.

Multi-phase heterogeneous materials experience these polarization mechanisms, as well as low frequency polarizations: interfacial spatial, bound water, and double layer. These property makes calculating the dielectric constant a difficult task. Daniels, 1996, reports that dry clay dielectric constant should be between two-six, and wet clay range between 15-40 [14]. These numbers can give us a guide, but with the different clay types we cannot be totally sure. Olhoeft, 1989, reports that kaolinite has a dielectric constant of 11.8 and quartz a dielectric constant of 4.5, but because clay pipe contain both quartz and kaolinite we need to consider the mixture when the dielectric constant is calculated. If a particular clay pipe contains more kaolinite than quartz we might be looking at a higher dielectric constant, than if the clay pipe contains more quartz than kaolinite. The raw materials of a vitrified clay pipe also include approximately 10 to 15 percent water [16]. Water has a high dielectric constant, which must be considered. Free water has a higher dielectric constant than bound water [15-16].

Water has a high dielectric constant because water is a polar molecule which is free to rotate along the direction of an applied electric field, allowing alignment of the water molecules electric dipoles. Bound water has a lower dielectric constant than free water contained in the pore spaces, because its water molecules are absorbed to the surfaces of particles and the dipoles are immobilized. So if we want to calculate the dielectric properties of clay pipes we need to account for the contributions to the dielectric constant from both bound and free water. So calculating the dielectric properties of clay pipes is complex, and there are many influencing factors [17-19].

Theory

Materials can be characterized by electric permittivity ε, electric conductivity σ, magnetic permeability μ, and magnetic conductivity σ^*. The frequency-dependence of all these properties is termed dielectric dispersion. We can assume clay to be as a homogeneous, isotropic, and lossless dielectric medium, although this is not totally the case. Dielectric properties of a material can be used to determine other material properties such as moisture content, and bulk density [20]. This section provides the background information regarding the theory of dielectric properties of materials in general. Dielectric properties can be interpreted both microscopically and macroscopically. Microscopically, dielectric properties represent the polarization ability of molecules in the material corresponding to an externally applied electric field. Macroscopically, dielectric properties are the relationship between the applied electric field strength E^* and the electric displacement D,* both externally measured. Dielectric properties are the collective terms of electric permittivity ε, electric conductivity σ, magnetic permeability μ, and magnetic conductivity $\sigma.^*$

Materials are described and classified by these properties into various types, such as metals and dielectrics [20]. Our research is with clay pipes, so the study will consider only isotropic materials. All of the properties of isotropic materials are described by first-order tensors. These quantities can be real or complex, depending on the nature of the material. When electric fields are applied to the clay and clay pipes, the quantities are generally complex. Complex electrical permittivity ε (F/m) describes the ability of a material to interact with an applied electric

field. It is defined as the ratio between the electric displacement D^* (C/m^2) and the electric field E^*(V/m). Generally,

$$\vec{D}^* = \varepsilon \, \vec{E}^* \tag{3}$$

where $\varepsilon = \varepsilon(\omega)$ for dielectric materials. It represents the ability of a material to permit an electric field to pass through the material [20]. For dielectric materials their frequency-dependent response is subject to applied electric fields, which is the result of the molecular polarizability. Their delayed and attenuated response is also observed and described as the dielectric dispersion phenomenon attributing to several polarization phenomena in the microscopic level. To account for these absorption and losses an imaginary part is needed in the dielectric description of the material property [40]. Therefore, the complex electrical permittivity (or complex permittivity) is defined as eq. (4).

$$\varepsilon = \varepsilon' + i(-\varepsilon'') = \varepsilon' - i\varepsilon'' \tag{4}$$

where ε' is the real part of ε representing the ability of a material to store energy that is carried by the electromagnetic field transmitting through it, and ε'' is the imaginary part representing energy absorption and loss. The negative sign defines ε'' as applied since energy dissipation/loss occurs to the clay pipe and clay in our research. A positive sign of ε'' would suggest that energy is being created. The measured values of ε' and ε'' mainly depend on measured frequency and temperature, while in some cases, as well as pressure [20]. For example, the Debye equations provide a frequency-dependent representation of ε' and ε'', satisfying the Kramers-Kronig relations, as eq. (5) and eq. (6).

$$\varepsilon'(\omega) = \varepsilon_i + \varepsilon_s - \varepsilon_i / (1 + (\omega\tau)^2) \tag{5}$$

$$\varepsilon''(\omega) = \omega\tau(\varepsilon_s - \varepsilon_i) / (1 + (\omega\tau)^2) \tag{6}$$

where $\omega = 2\pi f$ is the angular frequency, f is the temporal frequency, ε_i is the permittivity measured by electric (ac) current field at frequency $\omega = \infty$, ε_s is the permittivity measured by the electric (dc) current field at frequency $\omega = 0$, and τ is the characteristic relaxation time [21]. The relaxation time is usually represented by eq. (7).

$$\tau_t = \tau / 2\pi \tag{7}$$

Materials whose response can be described by the Debye equations are called Debye material.

We find Kramers-Kronig relations by using Fourier Transforms. We begin with the relation between the electric field and displacement at some particular frequency ω.

$$\vec{D}(x, \omega) = \varepsilon(\omega) \, \vec{E}(x, \omega) \tag{8}$$

where we note the two Fourier transform relations:

$$\vec{D}(x, t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{D}(x, \omega) \, e^{-i\omega t} \, d\omega \tag{9}$$

$$\vec{D}(\text{x, t}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{D}(\text{x}, \omega) \, \text{e}^{-\text{i}\omega\text{t}} \, \text{d}\omega \qquad (9)$$

and also, we have:

$$\vec{D}(\text{x}, \omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{D}(\text{x, t'}) \, \text{e}^{\text{i}\omega\text{t'}} \text{dt'} \qquad (10)$$

$$\vec{E}(\text{x, t}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{E}(\text{x}, \omega) \, \text{e}^{-\text{i}\omega\text{t}} \, \text{d}\omega \qquad (11)$$

$$\vec{E}(\text{x}, \omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{E}(\text{x, t'}) \, \text{e}^{\text{i}\omega\text{t}} \, \text{dt'} \qquad (12)$$

Therefore:

$$\vec{D}(\text{x, t}) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \varepsilon(\omega) \, \text{e}^{-\text{i}\omega\text{t}} \, \text{d}\omega \, \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \vec{E}(\text{x, t'}) \, \text{e}^{\text{i}\omega\text{t'}} \, \text{dt'} \qquad (13)$$

$$\vec{D}(\text{x, t}) = \varepsilon_0 \{ \vec{E}(\text{x, t}) - \int_{-\infty}^{\infty} G(\tau) \, \vec{E}(\text{x, t} - \tau) \, \text{d}\tau \} \qquad (14)$$

where I have introduced the susceptibility kernel:

$$G(\tau) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left(\frac{\varepsilon(\omega)}{(\varepsilon_0)} - 1 \right) \text{e}^{-\text{i}\omega\text{t}} \, \text{d}\omega \qquad (15)$$

$$G(\tau) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \aleph_0(\omega) \, \text{e}^{-\text{i}\omega\text{t}} \, \text{d}\omega \qquad (16)$$

where $\varepsilon(\omega) = \varepsilon_0(1 + \aleph_0(\omega))$. This equation is nonlocal in time unless $G(\tau)$ is a delta function, which in turn is true only if the dispersion is constant [20]. To understand this consider the susceptibility kernel for a simple one resonance model. In this case we have:

$$\aleph_0 = \varepsilon/\varepsilon_0 - 1 = \omega_p^2 / (\omega_0^2 - \omega^2 - \text{i}\gamma_0\omega) \qquad (17)$$

then,

$$G(\tau) = \frac{\omega_p^2}{2\pi} \int_{-\infty}^{\infty} \frac{1}{(\omega_0^2 - \omega^2 - \text{i}\gamma_0\omega)} \text{e}^{-\text{i}\omega\tau} \, \text{d}\omega \qquad (18)$$

This is an integral we can do using contour integration methods. We use the quadratic formula to find the roots of the denominator, and then write the factored denominator in terms of the roots:

$$\omega_{1,2} = -\text{i}\gamma \pm \sqrt{-\gamma^2 + 4\omega_0^2} / 2 \qquad (19)$$

$$\omega_{1,2} = (-\text{i}\gamma / (2 \pm \omega_0\sqrt{1 - u}) \qquad (20)$$

where $u = \gamma^2 / 4\omega_0^2$ and $\nu_0 \approx \omega_0$ as long as $\omega_0 >> \gamma/2$. Then,

$$G(\tau) = (2\pi i) \frac{\omega_p^2}{2\pi} \oint_c \left[\frac{1}{(\omega - \omega_1)(\omega - \omega_2)} \right] e^{-i\omega\tau} d\omega \qquad (21)$$

If we close the contour in the upper half plane, we have to restrict $\tau < 0$, because otherwise the integrand will not vanish on the contour at infinity where ω the positive imaginary part has. If we close the integrand in the lower half plane, $\tau > 0$ and we have:

$$G(\tau) = \omega_p^2 \, e^{-\gamma\tau/2} \, \sin(\nu_0)/ \nu_0 \, \theta(\tau) \qquad (22)$$

where this is a function to enforce the $\tau > 0$ constraint. Then we can use complex variables and Cauchy's theorem to continue to solve the problem [43][44]. We start by noting that $G(\tau)$ is real, and then we get:

$$\frac{\varepsilon(\omega)}{\varepsilon_0} - 1 = iG(0)/\omega - G'(0)/\omega^2 + \ldots \qquad (23)$$

from which we can conclude that $\varepsilon(-\omega) = \varepsilon^*(\omega^*)$. Note the even/odd imaginary/real in the series, and $\varepsilon(\omega)$ is therefore analytic in the upper half plane and so we have:

$$\frac{\varepsilon(z)}{\varepsilon_0} - 1 = \frac{1}{2\pi i} \oint_c \frac{\varepsilon(\omega')}{(\varepsilon_0 - 1)(\omega' - z)} d\omega' \qquad (24)$$

If we let $z = \omega + i\delta$, then we have:

$$1/(\omega' - \omega - i\delta) = P[1/(\omega' - \omega)] + i\pi\delta(\omega' - \omega) \qquad (25)$$

If we substitute this into the integral above along the real axis only, we have:

$$\frac{\varepsilon(\omega)}{\varepsilon_0} = 1 + \frac{1}{i\pi} P \int_{-\infty}^{\infty} \frac{\varepsilon(\omega')}{(\varepsilon_0 - 1)(\omega' - \omega)} d\omega' \qquad (26)$$

Although this looks like a single integral, because of the i in the denominator it is really two integrals. The real part of the integrand becomes the imaginary part of the result and vice versa. So what we have this is:

$$Re\left(\frac{\varepsilon(\omega)}{\varepsilon_0}\right) = 1 + \frac{1}{i\pi} P \int_{-\infty}^{\infty} Im \frac{\varepsilon(\omega')}{\varepsilon_0(\omega' - \omega)} d\omega' \qquad (27)$$

$$Im\left(\frac{\varepsilon(\omega)}{\varepsilon_0}\right) = -\frac{1}{\pi} P \int_{-\infty}^{\infty} Re \frac{\varepsilon(\omega')}{(\varepsilon_0 - 1)(\omega' - \omega)} d\omega' \qquad (28)$$

These are the equations that we know as the Kramers-Kronig relations [21]. A dimensionless representation is also used for defining the complex permittivity. The complex relative permittivity is defined by:

$$\varepsilon_r = \varepsilon/\varepsilon_0 = (\varepsilon' - i\varepsilon'')/\varepsilon_0 = \varepsilon'_r - i\varepsilon''_r \qquad (29)$$

where ε_0 is the electrical permittivity of free space, ε'_r is the dimensionless dielectric constant, and ε''_r is the dimensionless loss factor. It is only the dimensionless nature leading to the name "dielectric constant" since ε'_r is not a constant when considered over a range of frequencies [22]. The ratio between ε'_r and ε''_r is the loss tangent or dissipation factor, so when have:

$$\tan \delta = \varepsilon''_r / \varepsilon'_r = \varepsilon'' / \varepsilon' \qquad (30)$$

This dimensionless representation $(\varepsilon / \varepsilon_0 , \tan \delta)$ is simpler then and has an advantage over the original $(\varepsilon', \varepsilon'')$ representation because it clearly shows that the material is different from free space. Complex magnetic permeability μ describes the ability of a material to interact with an applied magnetic field. It is the ratio between the magnetic field flux density B and the magnetic field H.

$$\vec{B} = \mu \vec{H} \qquad (31)$$

where μ is a scalar for isotropic materials. The complex magnetic permeability is used when magnetic losses are present in the material [23][24].

$$\mu = \mu' - i \mu'' \qquad (32)$$

where μ' and μ'' are the real and imaginary parts of the complex permeability. The negative imaginary part of μ suggests the energy dissipation. A dimensionless relative complex permeability can be further defined as:

$$\mu_r = \mu' - i \mu'' / \mu_0 = \mu'_r - i \mu''_r \qquad (33)$$

where μ_0 is the permeability of free space. Definitions of various materials are listed in Table 1.

Table 1. Types of magnetic materials

Description	Criterion
Feromagnetic	$\mu_r > 10$
Paramagnetic	$1 < \mu_r < 10$
Diamagnetic	$\mu_r < 1$
Non-magnetic	$\mu_r = \mu'_r = 1, \mu''_r = 0$

Apparent electrical permittivity ε_a is defined by accounting for the direct current *conductivity loss in the representation of complex permittivity. Since the imaginary part transmitting through the material [24]. The total energy dissipation in the material can be* expressed by the dissipated or absorbed power using the complex poynting vector theorem and the Maxwell's equations. When dealing with electromagnetic fields a way is needed to relate the concept of energy to the fields [25]. This is done by means of the Poynting vector:

$$\vec{P} = \vec{E} \times \vec{H} \qquad (34)$$

where E is the electric field intensity, H is the magnetic field intensity, and P is the Poynting vector. The absolute value of Poynting vector is found to be the power density in an electromagnetic field. By using the Maxwell's equations for the curl of the fields along Gauss's

divergence theorem and an identity from vector analysis, we may prove what is known as the Poynting theorem. The Maxwell's equations needed are:

$$\nabla \times \vec{E} = - \partial \vec{B}/ \partial t \tag{35}$$

$$\nabla \times \vec{H} = \vec{J} + \partial \vec{D}/ \partial t \tag{36}$$

along with the material relationships:

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} \tag{37}$$

$$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M} \tag{38}$$

or for isotropic materials

$$\vec{D} = \varepsilon \vec{E} \tag{39}$$

$$\vec{B} = \mu \vec{H} \tag{40}$$

In addition, the identity from vector analysis,

$$\nabla \cdot (\vec{E} \times \vec{H}) = - \vec{E} \cdot (\nabla \times \vec{H}) + \vec{H} \cdot (\nabla \times \vec{E}) \tag{41}$$

Is needed. If P_A is to be the power density, then its surface integral over the surface of a volume must be the power out of the volume. So next do the negative of the surface integral to obtain P, the power into the volume:

$$\vec{P}_A = - \oiint \vec{E} \times \vec{H} \cdot \overrightarrow{dS}. \tag{42}$$

Now we can use Gauss's divergence theorem on the integral in equation (42), along with equation (43) , we have:

$$\vec{P}_A = - \oiint (\vec{E} \times \overrightarrow{H}) \cdot \overrightarrow{dS}$$
$$\vec{P}_A = \iiint - \nabla \cdot (\vec{E} \times \vec{H}) \, dV \tag{43}$$
$$\vec{P}_A = \iiint \vec{E} \cdot (\nabla \times \vec{H}) + \iiint \vec{H} \cdot (- \nabla \times \vec{E}) \, dV$$

Next, substituting from Maxwell's equations, we can obtain:

$$\vec{P}_A = - \oiint \vec{E} \times \vec{H} \cdot \overrightarrow{dS} = \iiint \vec{E} \cdot \vec{J} \, dV + \iiint \vec{E} \cdot \partial \vec{D}/\partial t \, dV + \iiint \vec{H} \cdot \overrightarrow{\partial B}/\partial t \tag{44}$$

Equation (3.42) is the Poynting theorem. The complex Poynting vector p is

$$\vec{P} = \tfrac{1}{2} \oint_s \ (\vec{E} \times \vec{H}^*)\ dS \tag{45}$$

where S is a closed surface and dS is a vector element of area directed outward from the volume V, H* is the conjugate of the magnetic field H. The divergence theorem provides:

$$\oint_s \ (\vec{E} \times \vec{H}^*)dS = \int_v \ \nabla \bullet (\vec{E} \times \vec{H}^*)\ dV. \tag{46}$$

From vector calculus we have

$$\nabla \bullet (\overrightarrow{E \times H}) = (\nabla \times \vec{E}) \bullet \vec{H}^* - (\nabla \times \vec{H}^*) \bullet \vec{E} \tag{47}$$

with Maxwell's equations $\nabla \times \vec{E} = i\omega\vec{B}$ and $\nabla \times \vec{H} = i\omega\vec{D} + \vec{J}$, Ohm's law $\vec{J} = \sigma \bullet \vec{E}$, and $\vec{B} = \mu\vec{H}$, the complex Poynting vector becomes:

$$\tfrac{1}{2} \oint_s \ (\vec{E} \times \vec{H}^*)\ d\vec{S} = \tfrac{1}{2} \int_V \ [(-i\omega\mu \bullet \vec{H}) \bullet \vec{H}^* + (i\omega\varepsilon \bullet \vec{E} - \sigma \bullet \vec{E})]dV \tag{48}$$

If we rearrange our equations, then:

$$\mathrm{Re}[\ \tfrac{1}{2} \oint_s \ (\vec{E} \times \vec{H}^*)(-d\vec{S})] = \omega/2 \int_v \ (\mu"\vec{H} \bullet \vec{H}^* + \varepsilon" \overrightarrow{E} \bullet \vec{E}^* + \sigma/\omega \vec{E} \bullet \vec{E}^*)\ dV \tag{49}$$

$$\mathrm{Im}\ [\ \tfrac{1}{2} \oint_s \ (\vec{E} \times \vec{H}^*)\ (-d\vec{S})] = \omega/2 \int_v \ (\mu'\vec{H} \bullet \vec{H}^* - \varepsilon'\ \vec{E} \bullet \vec{E}^*)\ dV \tag{50}$$

where - dS is the vector pointing toward the closed surface S and tangent to the surface boundary [25]. The real part of the complex Poynting vector is the dissipated energy P_{dis} absorbed by the material, which consists of three parts; magnetic loss, electric loss, and conductivity loss.

Since $\mu" = 0$ for non-magnetic materials, P_{dis} becomes:

$$\vec{P}_{dis} = \omega/2 \int_v \ (\varepsilon" + \sigma/\omega)\ \vec{E} \bullet \vec{E}^*\ dV = \omega/2 \int_v \ \varepsilon\vec{E} \bullet \vec{E}^*\ dV \tag{51}$$

and the effective dielectric loss factor is:

$$\varepsilon"_e = \varepsilon" + \sigma/\omega \tag{52}$$

So then we can write an effective conductivity which is defined as:

$$\sigma_e = \omega\varepsilon"_e = \omega\varepsilon" + \sigma \tag{53}$$

where $\sigma = \sigma_s$ is the electrical conductivity measured at the static frequency ($\omega = 0$). This conductivity is the real part of the complex conductivity [26]. So now that we know the effective dielectric loss factor, we can define the apparent complex permittivity as:

$$\varepsilon_a = \varepsilon" - i\varepsilon"_e = \varepsilon' - i(\varepsilon" + \sigma_s/\omega) \tag{54}$$

Definitions of materials based on our apparent complex permittivity are listed in Table 2.

Table 2. Types of dielectric materials

Description	Criterion
Perfect Dielectric	$\varepsilon" > 0, \ \varepsilon"_e = 0$
Imperfect Dielectric	$\varepsilon' > 0, \ \varepsilon"_e > 0$

Complex electrical conductivity σ describes the ability of a material to conduct an applied electric current, represented by the ratio between the electric current density $\vec{J}$ and the electric field $\overline{E}$.

$$\vec{J} = \sigma \bullet \vec{E} \tag{55}$$

where σ is the scalar electrical conductivity for isotropic materials. Following the previously shown energy treatment for the definition of the complex permittivity, the complex electrical conductivity can be defined as:

$$\sigma_a = i\omega\varepsilon_a = i\omega(\varepsilon' - i\varepsilon_e") = \sigma_e" + i\sigma" \tag{56}$$

where,

$$\sigma_e" = \omega\varepsilon_e" = \omega\varepsilon" + \sigma_s \tag{57}$$

$$\sigma" = \omega\varepsilon" \tag{58}$$

The defined effective conductivity is the real part of the complex apparent conductivity which can be defined as:

$$\sigma_e" = \omega\varepsilon_e" = \sigma_e \tag{59}$$

The D.C. conductivity, a frequency-independent term, is part of the apparent complex conductivity in the definition. The D.C. conduction effect is significant only in low-frequency or high-temperature situations, while it is insignificant in microwave frequency because:

$$\omega\varepsilon" > \sigma_s \tag{60}$$

By constructing this relationship, the definition regarding conductivity in complex apparent permittivity is connected to the complex apparent conductivity. This suggests that the behavior of this complex apparent conductivity is, by definition, similar to the one the complex apparent permittivity exhibits [26-27]. For example, in the Debye model, the real and imaginary parts of the complex apparent conductivity are:

$$\sigma_a = \sigma_e' + i\sigma" \tag{61}$$

$$\sigma_e" = = \sigma_s + (\omega\tau)^2 (\sigma_\infty - \sigma_s)/(1 + (\omega\tau)^2) \tag{62}$$

$$\sigma'' = \; = \; \omega\,\varepsilon_\infty + \; \omega\tau(\sigma_\infty - \sigma_s)\,/\,(1 + (\omega\tau)^2) \tag{63}$$

where σ_∞ is the permittivity measured by an alternating field at frequency $\omega = \infty$, and σ_s is the permittivity measured by the direct current field at frequency $\omega = 0$. Comparing σ_e' with $\omega\,\varepsilon_e''$ gives us:

$$\varepsilon_s - \varepsilon_\infty = \tau\,(\sigma_\infty - \sigma_s) \tag{64}$$

The relaxation time can be determined to be

$$\tau = (\varepsilon_s - \varepsilon_\infty)/\,(\sigma_\infty - \sigma_s) \tag{65}$$

The Debye-type behavior of complex electrical conductivity leads us to the loss tangent, which is:

$$\tan\delta = \varepsilon_e''/\,\varepsilon'' = \sigma_e'/\,\sigma'' = \sigma_e'\,/\,\omega\,\varepsilon' = \omega\,\varepsilon_e''/\,\sigma'' \tag{66}$$

Those with a high conductivity are considered to be conductors and those without conductivity are insulators (see Table 3). Nonconductive materials are also called loss-loss. Materials, with slight conductivity are called low-loss [25].

Table 3. Summaries of various materials by conductivity

Description	Criterion	Notes
Lossy	$0 < \tan\delta$	Electrical conductivity is present in the material.
Low-loss	$\tan\delta < 1$	General Definition
Lossless	$\tan\delta = 0$	Electrical conductivity is not present in the material.

We need to calculate the dielectric properties of the coaxial line, we use the procedure proposed by Nicholson-Ross-Weir method. The following equations will be a good place to start:

$$S_{11} = \Gamma(1 - T^2)\,/\,(1 - T^2\Gamma^2) \tag{67}$$

and

$$S_{21} = T(1 - \Gamma^2)\,/(\,1 - \Gamma^2 T^2) \tag{68}$$

These parameters we will obtain directly from the vector network analyzers. The reflection coefficient can be written as:

$$\Gamma = x \pm \sqrt{x^2 - 1} \tag{69}$$

where $\left|\Gamma\right| < 1$.

This is required for finding the correct root and in terms of the s-parameter:

$$X = S_{11}^2 - S_{21}^2 + 1\,/\,2S_{11} \tag{70}$$

The transmission coefficient can be written as:

$$T = S_{11} + S_{21} - \Gamma / (1 - (S_{11} + S_{21})\Gamma) \tag{71}$$

The permeability is then given as:

$$\mu_r = 1 + \Gamma / \Lambda (1 - \Gamma) \sqrt{1/\lambda_0^2 - 1/\lambda_c^2} \tag{72}$$

where λ_0 is the free space wavelength and λ_c is the cutoff wavelength. So then we have.

$$1/\Lambda^2 = (\varepsilon_r * \mu_r / \lambda_0^2 - 1/\lambda_c^2) = (1/2\pi L \ln(1/T))^2 \tag{73}$$

The permittivity can then be written as:

$$\varepsilon_r = \lambda_0^2 / \mu_r [1/\lambda_c^2 - (1/2\pi L - \ln(1/T)]^2 \tag{74}$$

The last two equations (71) and (72) have an infinite number of roots since the imaginary part of the term ln (1/T) is equal to j($\theta + 2\pi$ n) where n = 0, $\pm 1, \pm 2$,. this is the integer of (L/ λ_g). The permittivity can be calculated from the equations (73) and (74) which λ avoids determining the n values. However, this is only valid for permittivity measurement if we assume $\mu_r = 1$ [27]. This is what is assume in is research. We then have from equation (72).

$$1/\Lambda = \mu_r(1 - \Gamma) / (1 + \Gamma) \sqrt{1/\lambda_0^2 - 1/\lambda_c^2} \tag{75}$$

By setting this equation (73) equal to equation (72), the permittivity can be found:

$$1/\Lambda^2 = \mu_r^2(1 - \Gamma)^2 / (1 + \Gamma)^2(1/\lambda_0^2 - 1/\lambda_c^2) = \varepsilon_r * \mu_r / \lambda_0^2 - 1/\lambda_c^2 \tag{76}$$

If we now solve for ε_r, which yields:

$$\varepsilon_r = \mu_r (1 - \Gamma)^2 / (1 + \Gamma)^2(1 - \lambda_0^2 / \lambda_c^2) + \lambda_0^2 / \lambda_c^2 \ 1/\mu_r \tag{77}$$

Results

In this paper the research shows the dielectric properties of clay and clay pipes, which were measured using a two port coax and waveguide measurement using a computer that was running Microsoft windows. We connected the two port device to the Vector Network Analyzer and the computer as seen in Figure 1.

This research represents the results of complex permittivity measurement for dielectric materials at microwave frequencies. It was based on measuring S_{ij} scattering parameters using a Vector Network Analyzer by (TRL) calibration. In this research clay and clay pipes were used. Cylindrical samples specimens were made using a drill press. Dimensions of the specimens varied from three cm to four cm in diameter to four to five cm in height. A number of different conditions of the specimens were used for the measurements (1) saturated specimens with moisture on the inside for one month or more, (2) air dried specimens exposed to just room temperature and humidity, and finally (3) specimens were placed into saltwater (NaCl solution one M) for one month or more. Table 3-1 shows the calculated the percentage of moisture content for the

samples. The percentage of moisture content is the ratio between the amount of moisture in the specimen at the time of measurement and the absolute dry mass of the specimen. The samples were oven dried for two days (see Table 4).
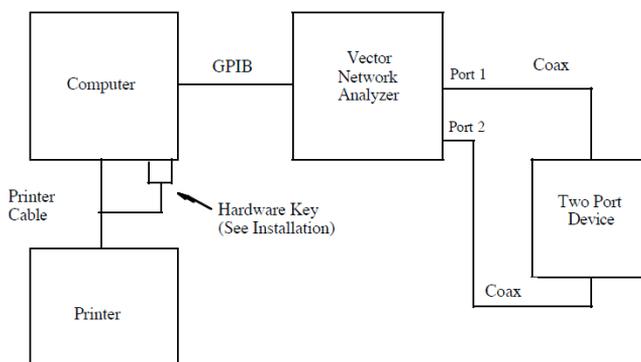
Fig. 1. System connections Two Port Setup.

Table 4. Percentage of moisture content, m [%].

	Clay and Clay Pipes	Wet	Dry mass	Percent of moisture m [%]
Water	Clay	27.244 grams	25.058 grams	8.723
Water	Clay Pipes	28.099 grams	26.063 grams	7.811
Saltwater	Clay	30.715 grams	28.353 grams	8.331
Saltwater	Clay Pipes	32.458 grams	30.061 grams	7.973

where $m = (W_n - W_s)/ W_s \times 100$; W_n = Mass of specimen at time of measurement; W_s = oven dried mass.

The Nicholson-Ross-Weir technique provides a way to directly calculate both permittivity and permeability from the s-parameters. It is probably the technique that is used the most to perform such conversion. If one wants to measurement the reflection coefficient and transmission coefficient then this requires all four s-parameters or a pair of s- parameters of the material under text to be measured [27-28]. Over two dozen runs were made for each sample, then a computer program was written that shows the average values for the dielectric constant, tangent loss, and conductivity (see Figures 2 through 12).
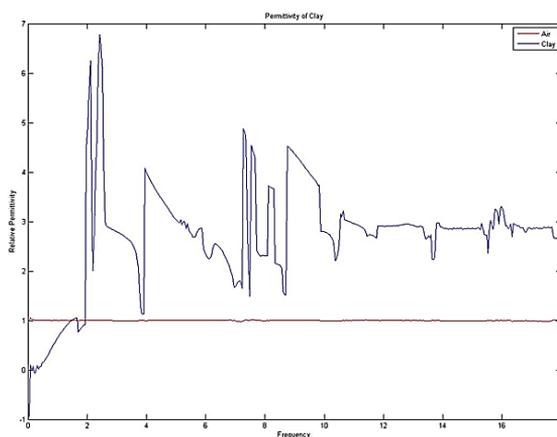
Fig. 2. Permittivity of Dry Clay (Frequency in Ghz)
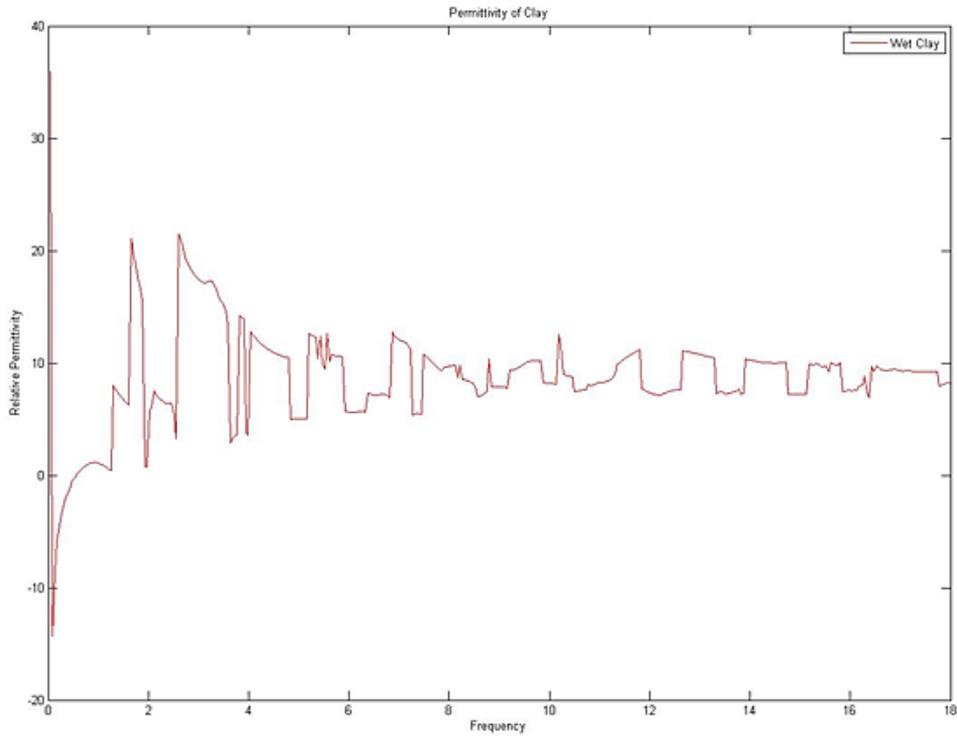
Fig. 3. Permittivity of Wet Clay (Frequency in Ghz)
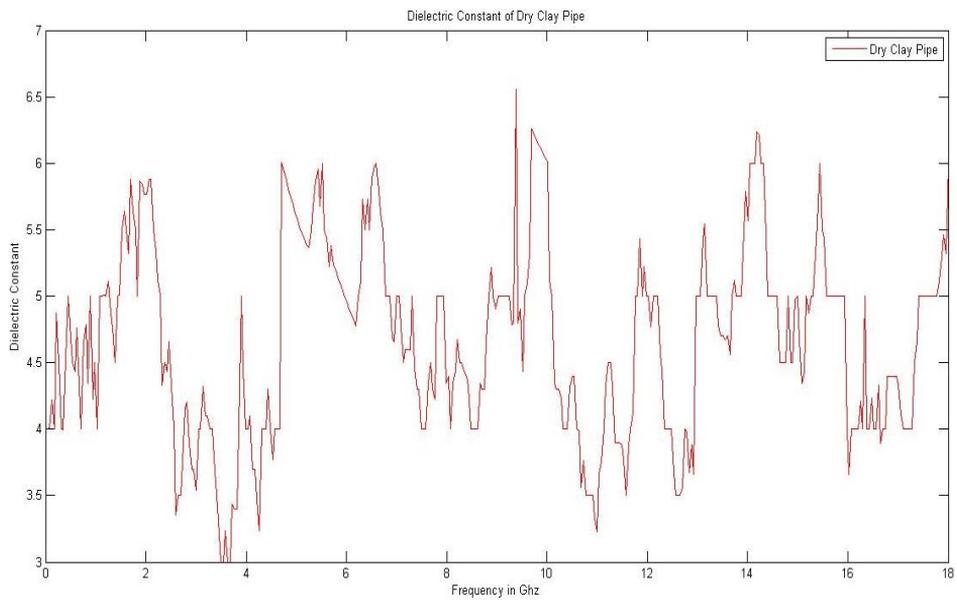
Fig. 4. The Dielectric Constant of Dry Clay Pipe (Frequency in Ghz)
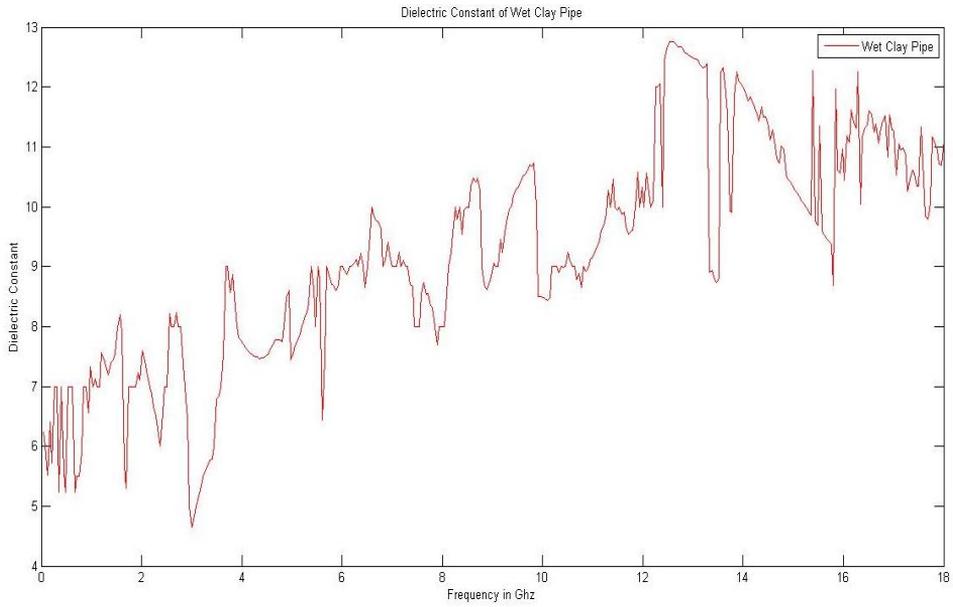
Fig. 5. The Dielectric Constant of Wet Clay Pipe (Frequency in Ghz)
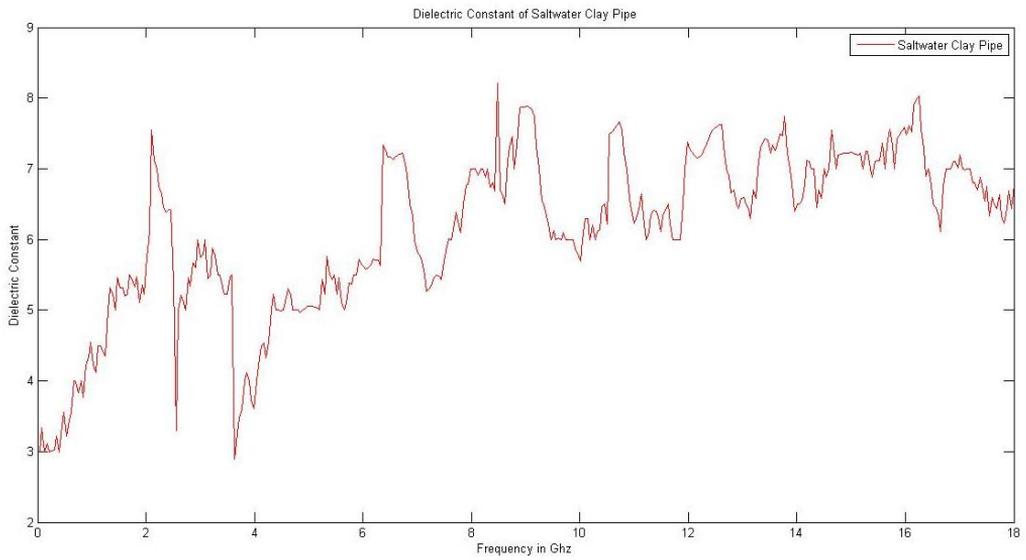
Fig. 6. The Dielectric Constant of Saltwater Clay Pipe (Frequency in Ghz)
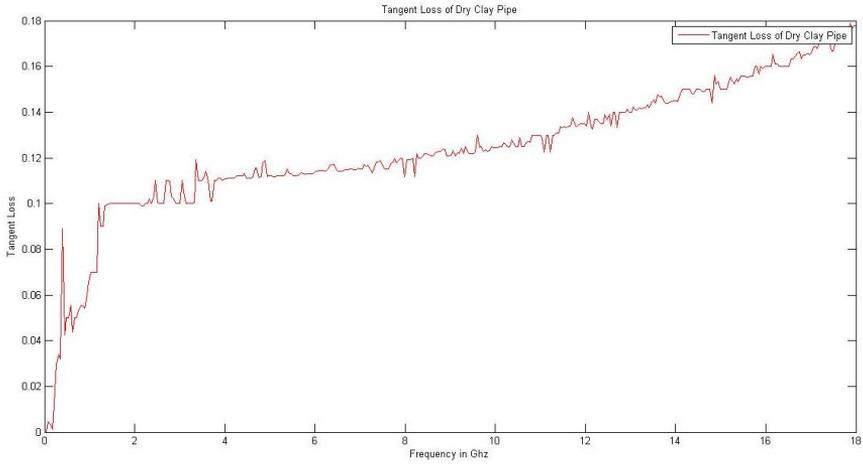
Fig. 7. The Tangent Loss of Dry Clay Pipe (Frequency in Ghz)
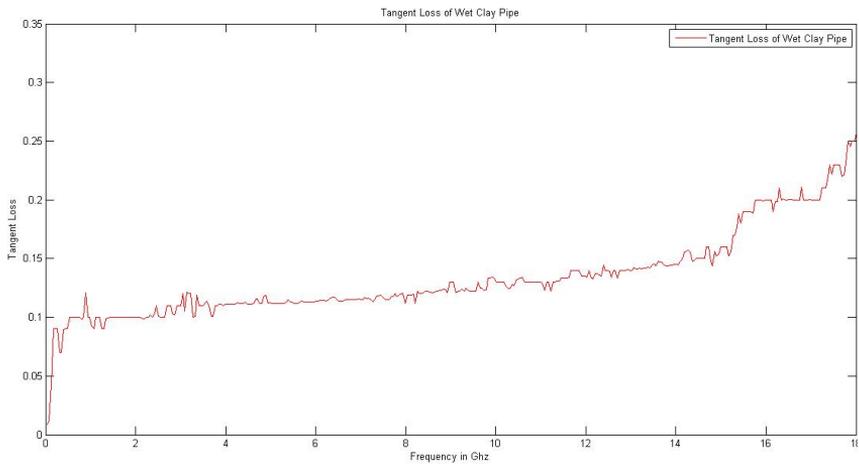
Fig. 8. The Tangent Loss Of Wet Clay Pipe (Frequency in Ghz)
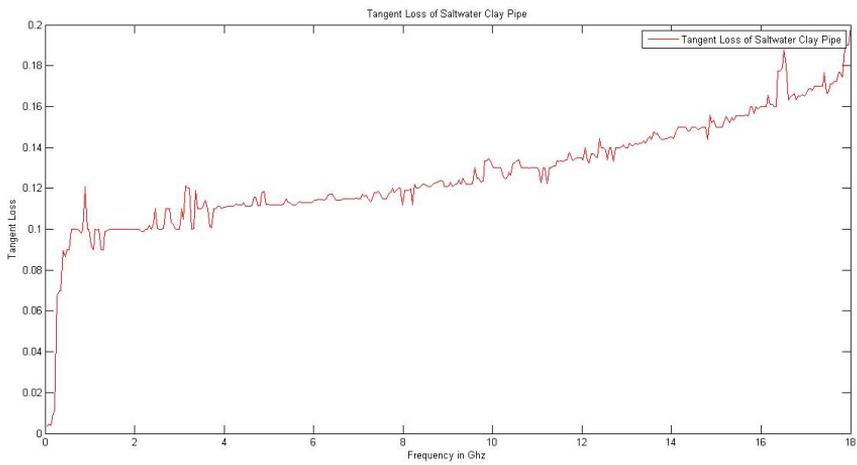
Fig. 9. The Tangent Loss Of Saltwater Clay Pipe (Frequency in Ghz)
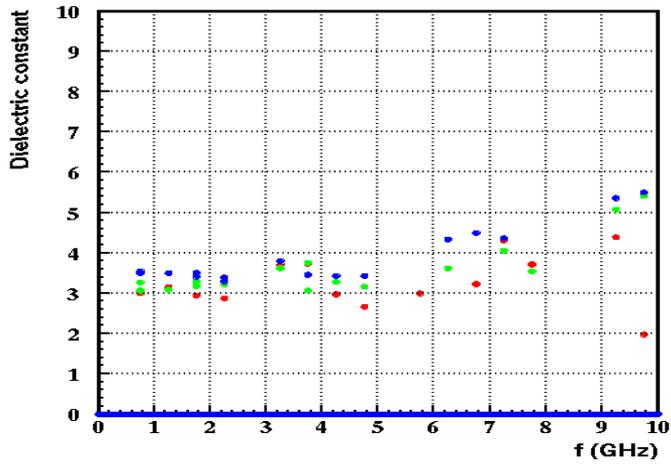
Fig. 10. Dielectric Constant of Clay. Red Dots Represent Dry Clay, Green Dots Represent Wet Clay, and Blue Dots Represent Saltwater Clay
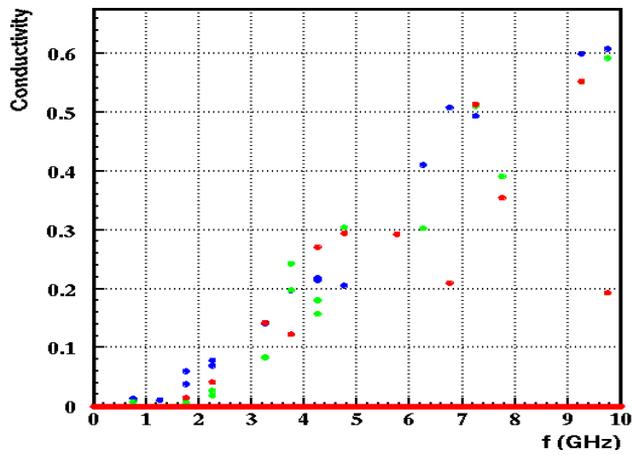
Fig. 11. Conductivity of Clay
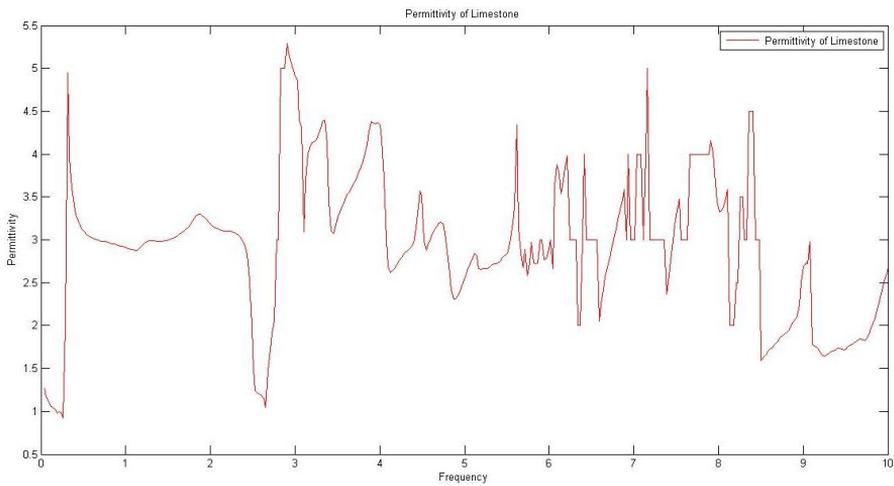
Fig. 12. The Permittivity of Limestone (Frequency in Ghz)

Summary

The dielectric constant of a material is not a constant, but is a function of many factors. The dielectric constant is in turn a function of frequency, temperature, local fields, applied field strength. The dielectric conductivity is also affected by the same factors that influence the dielectric constant [28]. Moisture and chloride are the two constituents which have the most effect on the dielectric properties of clay pipe and clay. In general, the real part of the dielectric constant is larger when it is easier for the material to polarize, meaning that the ions are mobile and there is little crystallization. The addition of chlorides increases the dielectric constant, as does the amount of water. The dielectric constant decreases over curing time, because the amount of water decreases during this time [29-30].

Clay pipes are a mixture of different clay minerals, which makes it a multi-phased heterogeneous material. Dielectric constant is a measure of the polarizability of a material. Polarization is the spatial separation of charges due to an applied electric field. The process that cause polarization depend on the frequency of the applied electric field. Homogeneous materials experience only high frequency polarization mechanisms. [31].

Multi-phase heterogeneous materials experience these polarization mechanisms, as well as low frequency polarizations: interfacial spatial, bound water, and double layer. These property makes calculating the dielectric constant a difficult task. If a particular clay pipe contains more kaolinite than quartz we might be looking at a higher dielectric constant, than if the clay pipe contains more quartz than kaolinite. The raw materials of a vitrified clay pipe also include approximately 10 to 15 percent water. Water has a high dielectric constant, which must be considered. Free water has a higher dielectric constant than bound water [32].

Water has a high dielectric constant because water is a polar molecule. This means that water is free to rotate along the direction of an applied electric field. This allows alignment of the water molecules electric dipoles. Bound water has a lower dielectric constant than free water. So if we want to calculate the dielectric properties of clay pipes we need to account for the contributions to the dielectric constant from both bound and free water. So calculating the dielectric properties of clay pipes is complex, and there are many influencing factors [32].

Conclusions

In conclusion, it appears that at under dry conditions, the dielectric constant of clay pipes does not vary much over the measured frequency range. The dielectric constant of dry clay pipe range between 3 to 7 (see Figure 3.4). However, the change of the dielectric constant of clay pipe becomes significant as the moisture level increases. The dielectric constant of wet clay pipe changes significantly from dry clay pipe. The dielectric constant of wet clay pipe ranges between 6 to 13 (see Figure 3.5). Moisture content is one of the major constituents which influence the electromagnetic properties of clay pipe. Loss factor of clay pipe is the imaginary part of the complex permittivity. The loss factor is divided by the dielectric constant over the frequency range to obtain the loss tangent. The loss tangent of clay pipe increases as frequency increases, the effect of water on the lossyness of clay pipe is shown in the figures 3.7-3.9, as the loss tangent of clay pipe specimens with higher moisture content show higher loss tangent values than those with less moisture content. The relative permittivity of clay pipes is frequency dependent. This could be a result of polarization effects that take place at different frequencies. The clay pipe have a high specific internal surface area with polarizable cations within the interlayers and on the surface. These properties of clay pipe are controlled by the cation exchange capacity [34].

The significance of conductivity is that the penetration depth of the wave in clay is inversely proportional to the conductivity. The conductivity in clay varies depending varies depending on the type of ingredients used in the sample. Saltwater has almost the same effects on clay pipe as water. The dielectric constant of clay pipe in saltwater is almost the same as the

dielectric constant of wet clay pipe (see Figure 3.6). In general, the dielectric constant of saltwater is just a little less than the dielectric constant of wet clay pipe. Saltwater has a more significant influence on the loss part of the Dielectric constant than the real part (See Figure 3.2-3.12) [33- 36].

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