APPLICATION OF DIELECTRIC MEASUREMENT TO SATURATED SYSTEMS AND FLUID FLOW THROUGH POROUS MEDIA

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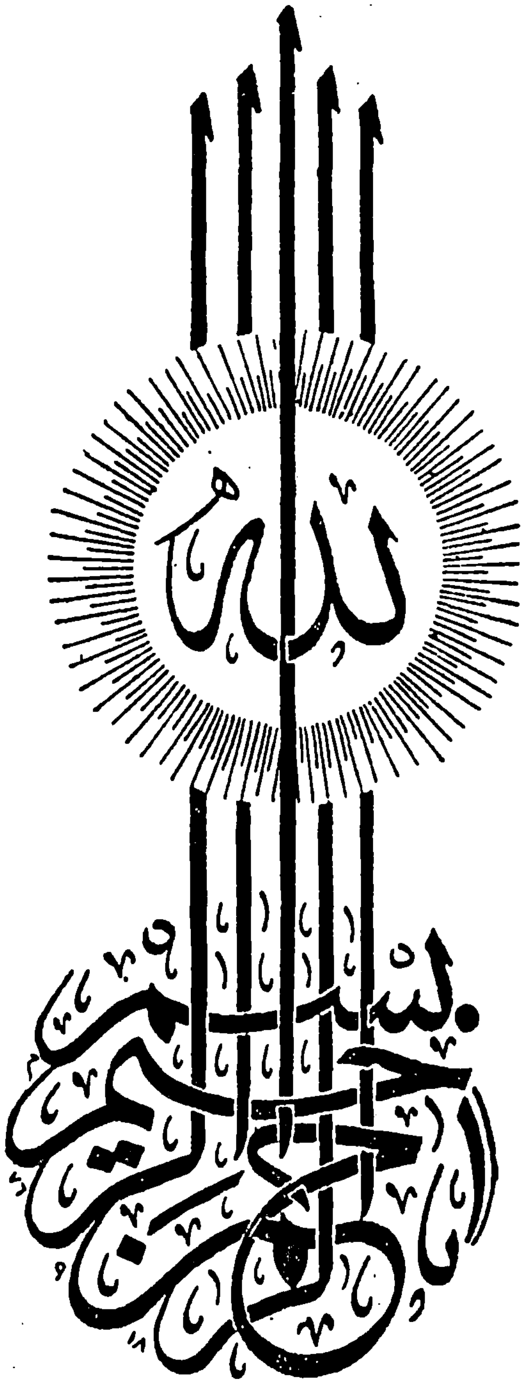
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بسم الله الرحمن الرحيم

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CHAPTER I

INTRODUCTION

Determination of the amount and distribution of the aqueous component as a percentage of pore volume (water saturation and water content) in natural soils has been of fundamental importance in many research and applied science areas. This is of particular significance in oil exploration, soil science, hydrology and engineering studies.

Some of the industrial applications which have promoted this research include the exploitation of oil reserves and the increased interest in secondary and tertiary recovery . Secondary recovery is usually achieved by water injection producing water and hydrocarbon-bearing zones. The accurate determination and control over the degree of saturation, as well as the understanding of the system's behavior, influence the productivity of an oil field and the amount of hydrocarbons which is extractable from the reservior.

It is known that some 75% of the earth's fresh water is held in polar ice caps and glaciers, while less than 2% is in surface water, such as lakes and streams, and a lesser amount is contained in the generally unsaturated topsoil. This leaves approximately 22% of our planet's fresh water permeating the porous rocks and subsoils below the ground surface. It is this amount which is called groundwater. In many geological regions, groundwater constitutes an important source of fresh water for domestic or industrial use. Exploitation of groundwater as an adequate water supply could be a prerequisite for the development of settlements and industries at certain localities.

Historical Outline

The determination of water saturation or water content can be achieved by direct or indirect methods. The direct technique entails sampling and drying methods where the "moist" and "dry" weights are determined and the water content is evaluated from the knowledge of the density. This sampling method is destructive and may disturb an observation or experimental plot to distort the results. To preserve the natural conditions for the samples, many researchers prefer indirect methods such as:

1. Electrical Resistance: The resistivity logs are electric logs which are used to determine the hydrocarbon versus water-bearing zones and to indicate a permeable zone. Electrical conductivity of moist porous media is due primarily to the permeating fluid rather than the solid matrix. Thus, it depends on the volume content of the fluid. However, it was found that this method is likely to be of limited accuracy (Hillel, 1980).

2. The Neutron Scattering Method measures the hydrogen ion concentration in a formation. In clean formations (i.e. shale-free) where the porosity is filled with water or oil, the neutron log measures liquid-filled porosity. This method has gained widespread acceptance for monitoring the profile of water content in a field. Some disadvantages have limited the use of this technique. Improper use of the equipment can be hazardous, and it is costly for extensive use.

3. Gamma-ray Absorption measures the natural radioactivity of a formation. The gamma-ray scanner (Hillel, 1980) is used for measuring soil moisture. This technique offers several advantages over the neutron scattering method since it allows much better depth resolution in the measurements. However, the field device is too cumbersome for general usage and the problems

associated with the use of gamma-ray equipment are similar to those of neutron scattering.

4. Other approaches include techniques based on the dependence of soil thermal properties upon water content, the use of ultrasonic waves, and radar waves in connection with the remote sensing. However, these methods are limited in application since they deal with surface interpretation only and are not yet practical for routine use in the field.

A more reliable indirect experimental method uses the dielectric constant of a porous system to calculate water saturation and water content using mixing laws, which interrelate the composite dielectric constant of the porous media to those of its components. The dielectric measurement technique employing high-frequency electromagnetic waves is based on the large contrast which exists between the dielectric constant of water and those of other earth formations. The use of high-frequency (microwave) techniques has been promising in studying the distribution of water and oil in field cores (Brost et. al, 1981; Pascal, 1983). However, measurements using this technique require critical selection of the most suitable mixing laws for a particular case. In reality, no single mixing law has been reported suitable for calculating water saturation for all porous media under many different conditions.

This investigation was undertaken to compare the available mixing laws under differing conditions using fully and partially saturated porous samples of consolidated as well as unconsolidated materials. Different miscible and immiscible fluids replacing each other were used in the porous system to identify the set of conditions under which each law can provide reliable estimates. The investigation program was divided into four sections as follows:

1. The determination of the mixing law that could be used to calculate the solid matrix dielectric constant from the measurement of the dry sample.

When ϕ_s <<1 the term containing $\phi_s^{10/3}$ may be ignored, and Equation 2.2 reduces to the form which was later obtained by Weiner (1912) as the following equation

$$\frac{\varepsilon - \varepsilon_f}{\varepsilon + 2\varepsilon_f} = \frac{\varepsilon_s - \varepsilon_f}{\varepsilon_s + 2\varepsilon_f} \qquad \phi_s \tag{2.3}$$

This expression made calculations of the dielectric constant much easier but still applied only to particles of regular arrangements. For materials with randomly distributed particles, Wagner (1914) derived the same equation as Weiner's (Equation2.3) with a similar requirement of low porosity.

Since Equation 2.3 was limited to cases where ϕ<<1, a situation which is very rarely found in nature, there has always been a nagging demand for a formula that does not necessitate such a limitation. Bruggeman (1935) extended Equation 2.3 to concentrated dispersion on the basis of the following assumptions. First, Equation 2.3 holds for infinitesimally increasing processes in concentration of the dispersed phase. Second, the final high concentration of the dispersed system is attained by a succession of these processes. These assumptions, with the mathematical derivation discussed in Chapter IV, led to the following formula:

$$\frac{\varepsilon - \varepsilon_f}{\varepsilon_s - \varepsilon_f} \left(\frac{\varepsilon_s}{\varepsilon}\right)^{A} = \phi \tag{2.4}$$

The exponent A is called the depolarization factor and for spherical particles A = 1/3. Equation 2.4 is the Effective Medium Theory (EMT) or is sometimes referred to as Brugeman's Equation.

Lichtencker and Rother (1937) proposed a general empirical formula that interrelates the dielectric parameters of a medium. The form of the equation is

$$\varepsilon = [\, \varepsilon^{c}{}_{f}\,\phi + \varepsilon^{c}{}_{s}\,(1 - \phi)\,]^{1/c} \tag{2.5}$$

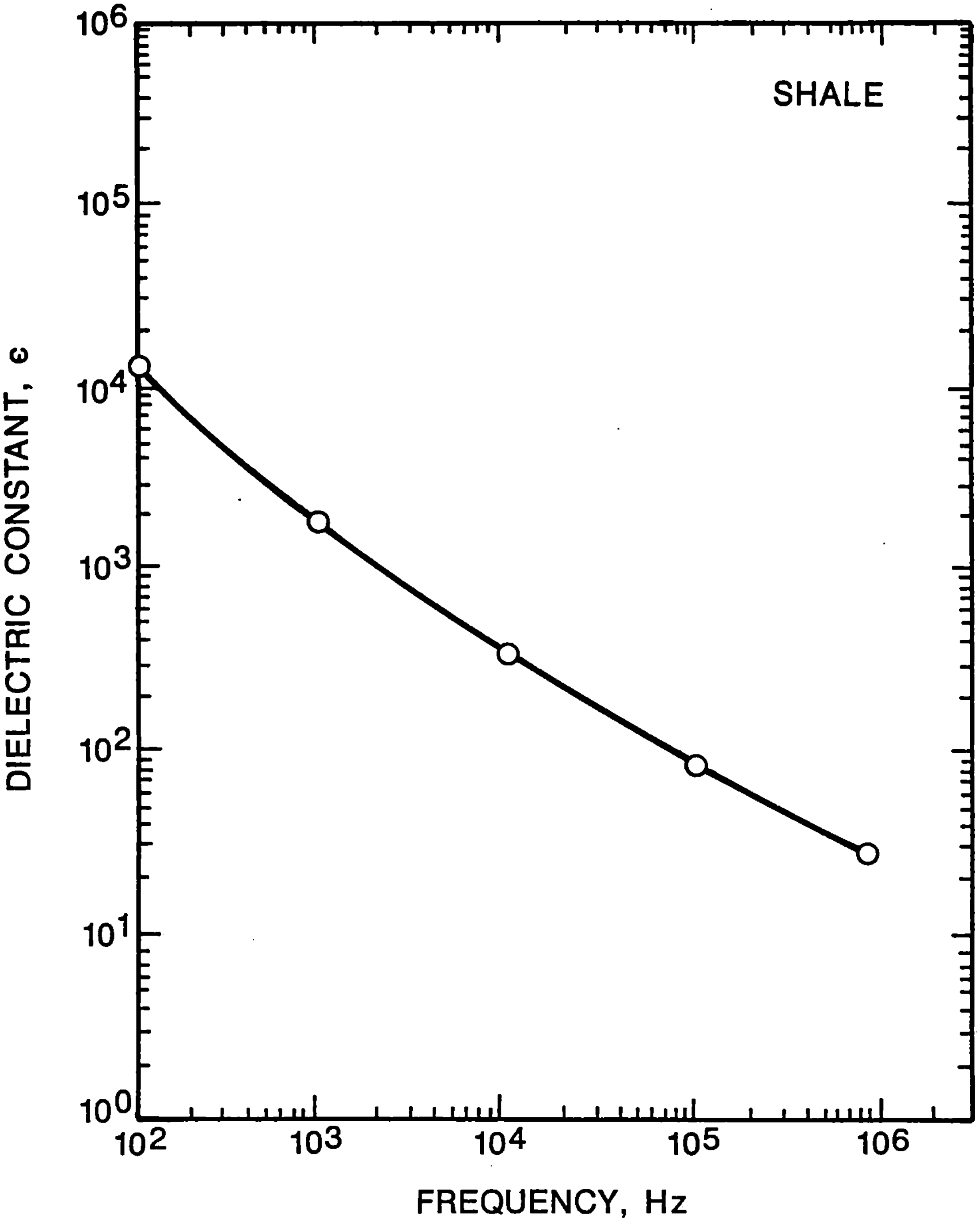


Figure 1. Dielectric Constant of Shale as a Function of Frequency. At low frequencies, the dielectric constants become very high (Scott, et al., 1967).

The exponent c is empirically determined. When $c = .5$ the equation is called the Square Root Equation (SRE). It has the same form as the Complex Refractive Index Method (CRIM) of Schlumberger, where when $c = 1$ it is called Volume Fraction Equation (VFE) (Birchak et al., 1974). Since the above equations are applicable only to two-component systems it was necessary to obtain an equation that can be used with systems including more than two components (e.g. solid, water and other fluid). This was made possible by extending Equation 2.5 (Meador and Cox, 1975) as follows:

$$\varepsilon = [\, s_w \phi \; \varepsilon_w{}^c + (1 - s_w)\phi\, \varepsilon_f{}^c + (1 - \phi)\, \varepsilon_s{}^c]^{1/c} \tag{2.6}$$

where s_w is the water saturation of the medium (the percentage of the pore volume filled by water).

Modeling of porous media has recently undergone a revival in an effort to learn more about how formation, pore space, and fluid content control the measured electrical properties of rocks. Although Bergman (1982) showed the difficulties associated with the determination of the composite dielectric constant of a material, additional developments made (Sen et al., 1981) using the effective medium theory. Sheng and Callegari (1984) used the "differential effective medium" approach to model simultaneous velocity, attenuation and conductivity in porous media. In 1983, Chylek and Srivastava derived an expression for the effective dielectric constant of a composite medium considering the contributions from both the electric and magnetic dipole moments. They showed that the form of the size distribution of small metallic particles determines the values of the volume fraction at which a sharp increase in the absorption of a composite material occurs.

Experimental Work on Dielectric Techniques

Pascal (1964) suggested use of electromagnetic wave propagation to study electrical properties of porous systems. The parameters which constitute the electrical properties of any medium are the conductivity (σ) and the dielectric constant (ε), which are usually expressed in a combined form known as the complex dielectric constant, ε^*

$$\begin{aligned} \varepsilon^* &= \varepsilon' + i\varepsilon'' \\ &= \varepsilon' + i\sigma/\omega \end{aligned} \tag{2.7}$$

where ω is the angular frequency of the electromagnetic field with which the system interacts. So, the behavior of the field is directly affected by the complex dielectric constant. The imaginary part, (ε''), in Equation 2.7 is dominant at low frequencies. For frequencies above 20 MHz both real and imaginary parts are measurable. For many materials the real part of Equation 2.7 increases by several order of magnitudes as the frequency is lowered from the megahertz range to a few hertz. Unrealistic values of dielectric constants as large as 10^3 or 10^5 have been reported by many workers (Fricke, 1925; Dunlap and Makower, 1945; Van Hipple 1954). The odd results have been attributed (Klein and Sill, 1982) to polarization at low frequencies (10-1000 Hz) which causes dispersion and a high dielectric constant as shown in Figure 1. On the other hand, the dielectric constant at frequencies above 200 MHz has been shown to be virtually constant (Poley et al., 1978) as shown in Figure 2. Several models for the high-frequency electrical response of porous sytems were recently formulated (Lysne, 1983; Pascal, 1983). Laboratory measurements by Lange (1983) and Shen et al., (1985) showed the effects of salinity, frequency and bound water on the dielectric constant of porous systems. From the foregoing review it appears that microwave frequencies offers an attractive new method for system evaluation.

The techniques used for measuring the dielectric constant of a system at high frequencies are reflection, transmission or resonant cavity methods. The reflection method gives satisfactory results for low- and medium-loss samples, but not for high losses, for which the transmission method seems to be ideal. The resonant cavity technique gives good results for medium- and low-loss samples. For high-loss samples, the sample size has to be reduced to maintain the accuracy of the measurements. Recently a method called

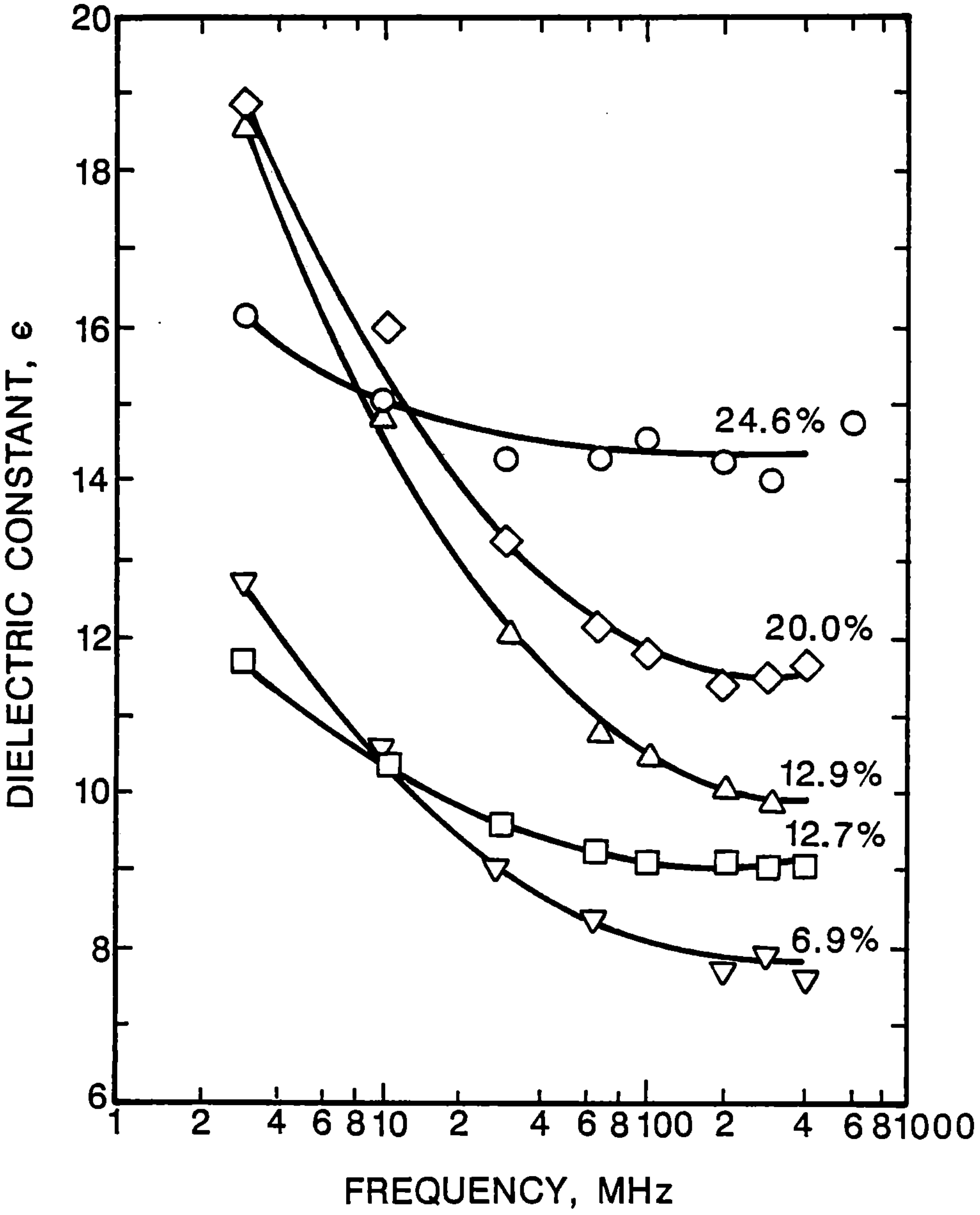


Figure 2. Dielectric Constant of Water Saturated Sandstone as a Function of Frequency. At high frequencies constant values were achieved. The percentages represent the porosity of the sample (Poley et al., 1978).

the S-parameter technique which combines the reflection and transmission method and overcomes the disadvantages of both, has been developed. This technique is applicable both to transmission lines and waveguides and a detailed discussion is presented in two recent papers (Rau and Wharton, 1982; Shen, et.al., 1985). Meador and Cox (1975) at Texaco developed a probe by which they measured the dielectric constant. A similar logging instrument called DPT (Deep Propagation Tool) was offered by Schlumberger (Huchital, et al., 1982). The probes operate at 10-50 MHz. Schlumberger also developed a somewhat different probe called EPT (Rau and Wharton, 1980) which operate at frequency of 1.1 GHz and employs waveguide type antennas mounted on a deployable sidewall pad.

Dielectric meaurements for different geological material (Poley, et al., 1978) were conducted using samples which were cut from core sections to fit into a transmission line. Frequencies were varied from 1500 Hz up to about 1.8 GHz. Core samples were saturated with water of different degrees of salinity. It was shown that at low frequencies the values of dielectric constants are very large. At frequencies higher than 200 MHz the dielectric consant was independent of frequency. Another conclusion of Poley et. al was that in the high frequency range the dielectric constant values were independent of water salinity. Later work showed that salinity does affect the dielectric constant measurements and the above conclusions are acceptable only for fresh water (Lange and Shope, 1981; Rau and Wharton, 1982).

Evaluation of the Eperimental Results

Sen et al., (1981) used glass beads saturated with water and methanol to study some of the mixing laws. They concluded that the EMT formula is most accurate in evaluating the effective dielectric constant of two-component systems.

Rau and Wharton (1982) considered both dielectric constant and dielectric loss for different materials including brine. The article concluded that dispersion is present in a lossy rock formation at VHF. Below those frequencies such effects were not observed. The mixing law which was claimed to be the most accurate was SRE. The question of which is the adequate mixing law is not answered precisely. In their extensive work Shen et al. (1985) presented recent results concerning the prediction of the composite dielectric constant compared to measured values. The S-paramenter technique was used to determine dielectric constants of porous media. Seventeen core samples were used with different frequencies and different water salinities. The conclusion which was reached showed that modified CRIM and EMT fit the data. One of the purposes of this investigation is to resolve the uncertainity and conflicting claims associated with the application of the mixing laws.

Dielectric properties of soils at UHF and microwave frequencies were studied to determine their water content (Hoekstra and Delaney 1974). Four types of soils were used for frequency ranges from .1 GHz to to 26 GHz. The water content of the soil was varied as well as the temperature. Results showed that the relation between volumetric water content and the dielectric constant is relatively independent of soil types. The dielectric constant of water in soil decreases at temperatures above zero °C. Below the freezing point the phase composition of water in soil determines the temperature dependence of the dielectric constant. In a complementary work done by Topp et al., (1980), a time-domain reflectometer (TDR) was used to measure the dielectric constant of a wide range of soil specimens. Frequencies used were between 1 MHz and 1 GHz. Beside the results mentioned by Hoelstra and Delaney, an empirical formula relating the dielectric constant to the volumetric water content was suggested.

CHAPTER III

EXPERIMENTAL TECHNIQUE

This chapter is concerned with the elements of the experimental arrangement, their functions and applications to the measurement. The procedure used to determine the dielectric constant from the propagation of the electromagnetic (EM) wave through a transmission line is discussed along with the methods used to prepare samples. Finally, the experimental uncertainty of the measurements of various parameters are presented and related to evaluation of various mixing laws.

Apparatus

The experimental set up is designed to determine the time of propagation of a monocycle impulse, with microwave frequency, through a standarized coaxial transmission line. The impulse propagates with a speed close to that of the speed of light and requires sophisticated equipment to analyze the small traveltime of the signal through the coaxial line. The impulse is displayed on an oscilloscope screen after being averaged and sampled.

A schematic drawing of the apparatus used in the investigation is illustrated in Figure 3. It consists of a microwave impulse generator with power divider which channels the impulse to a boxcar and a coaxial transmission line. A sampling integrator is connected to the boxcar which is connected to a waveform digitizer in the oscilloscope. A delay line is used to give the boxcar enough time to be triggered.

Following is a brief description of each component of the apparatus and its main function.

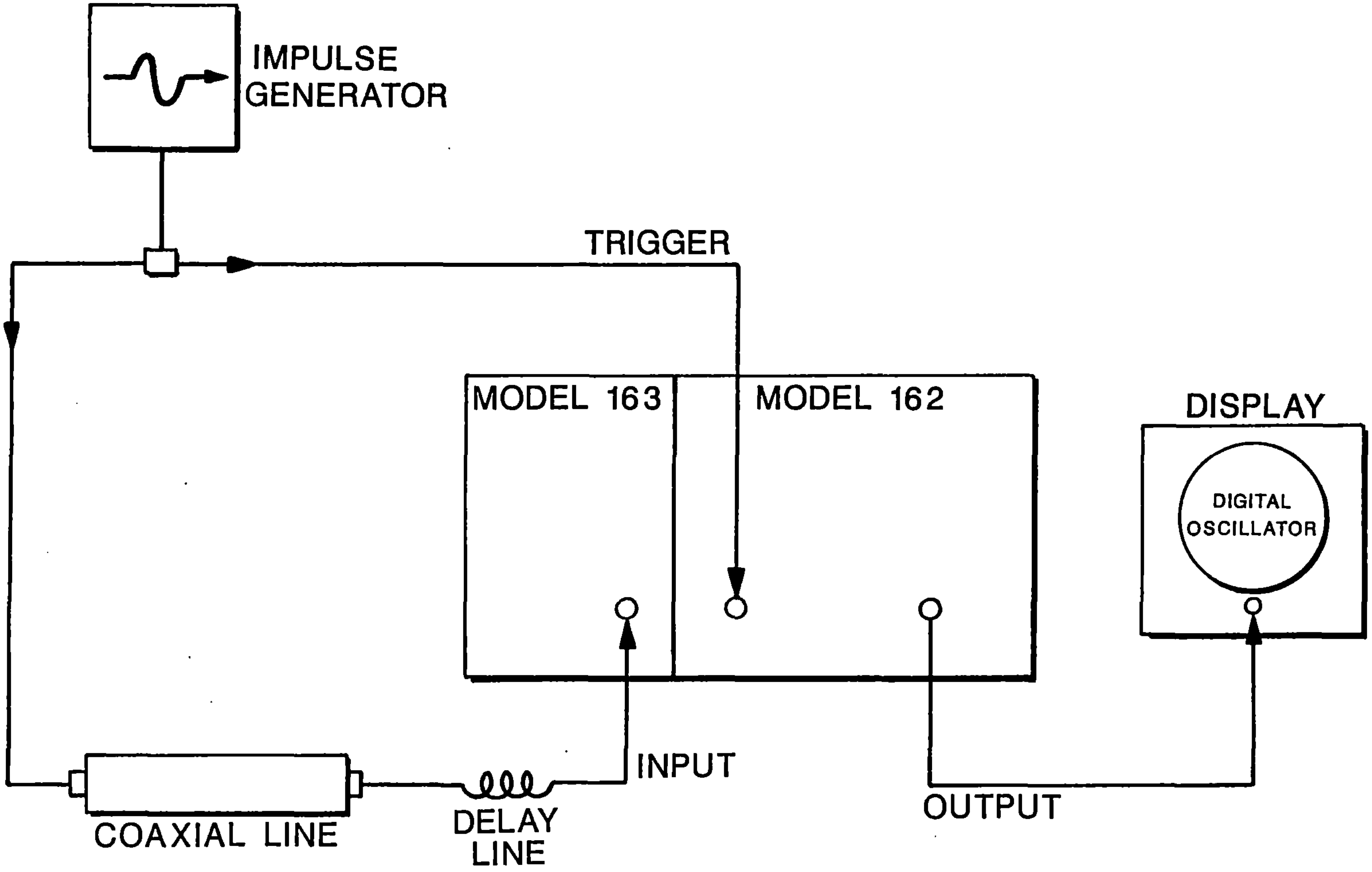


Figure 3. A Schematic Diagram For The Measuring Apparatus

Following is a brief description of each component of the apparatus and its main function.

Impulse generator

This component provides a monocycle impulse signal in the microwave frequency range. As shown in Figure 4, the generator consists of three parts.

i) An LMS55 Timer is used as a pulse generation in this circuit. The output (pin #3) is connected to the input (pin #5) of the 74121 multivibrator.

ii) An ECG 74121 monostable multivibrator is used to generate a pulse. R_1 controls the pulse width accuracy and repeatibility. The voltage is decreased from +15V to +5V by R_2, because the integrated circuit 74121 operates on +5V supply. An external capacitor C_1 is used to determine pulse width of the output signal. A zener diode D_1 is used to stabilize the +5V dc voltage supplied to the multivibrator.

Pulse triggering occurs at a particular voltage level and is not directly related to the transition time of the input pulse. Once fired, the output (Pin #6) is independent of the input (Pin #5) and is a function of the timing components (R_1 and C_1). So input pin #5 is used for triggering only. With R_1 connected to V_{cc}, improved pulse width accuracy and repeatability was acheived. Output (Pin #6) was used as an input connected to the monocycle generator.

iii) A monocycle generator Model AVA (Avtech Electro system Ltd.): The input singal to the AVA monocycle generator is a low-level, slow-speed pulse that is used for triggering purposes. This input circuit is a Transistor-Transistor Logic (TTL) signal with a 2-5 V level. The amplitude of the output signal is ≥, 20 V_{pp} (peak to peak voltage). The power supply is a +15V (150 mA) and the frequency range is 200-400 MHz. The

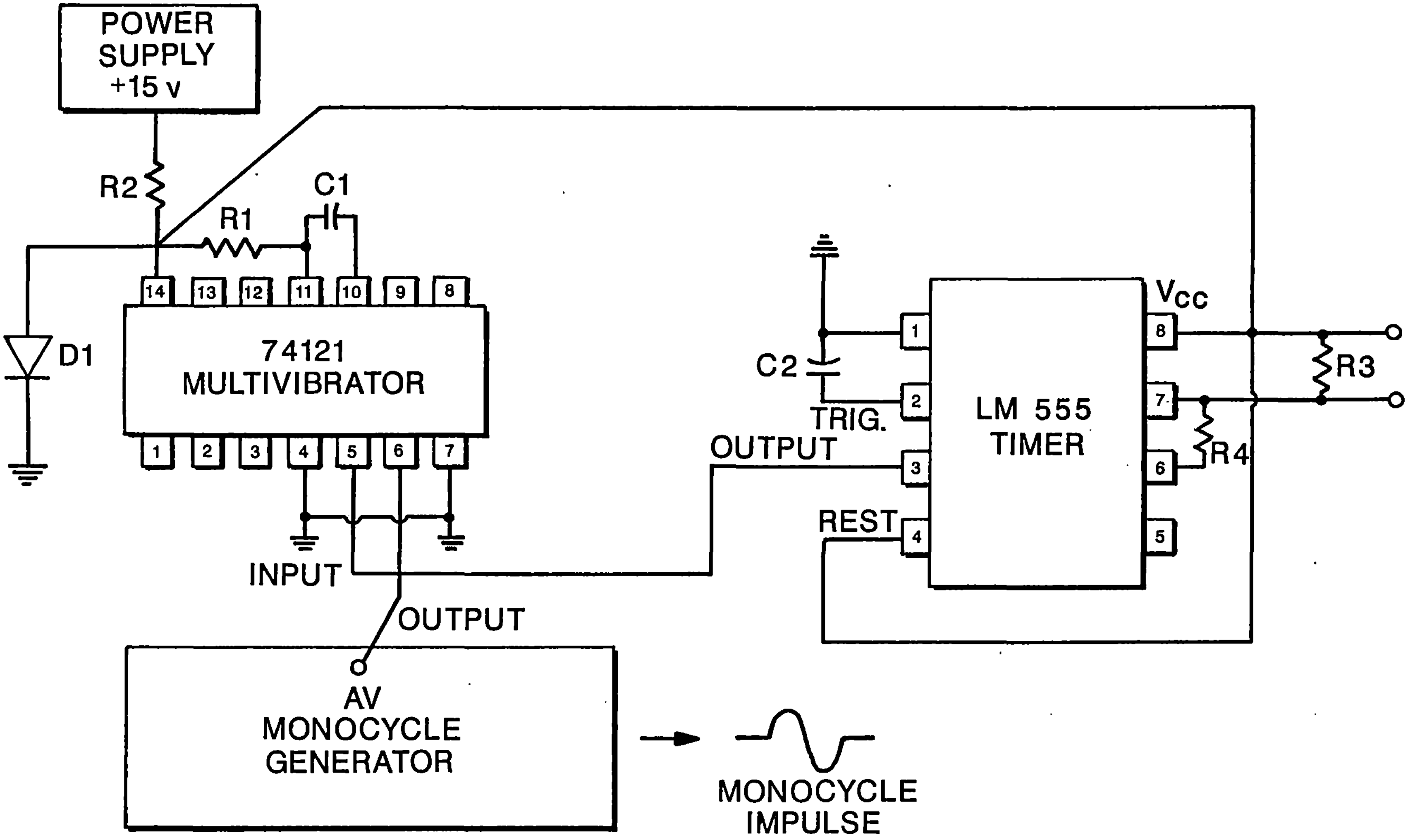


Figure 4. A Schematic Diagram For The Impulse Generator

The Boxcar Integreator

The boxcar integrator (Princeton Applied Research, Model 162) controls sampling and averaging of the input signal. It repeatedly measures the amplitude of a specific point on a repetitive waveform for the required averaging number. The integrator is combined with a Sampling Integrator Module (Model 163) to form a gated signal recovery system which synchronously samples the input signal with an aperture that can be fixed at any point on the signal. The signal passed through the aperture is applied to a variable time constant integrator, the output of which is the average number of repetitions of the input signal.

The main frame (Model 162) performs most of the functions while Model 163 uses a Tektronix Sampling Head S-2 to achieve aperture resolution. The Sampling Head has an impedance of 50Ω, aperture duration of 75 picoseconds and averaging capability up to 10^4 samples.

Coaxial Transmission Line

In order to direct the transmitted signals, microwave energy is guided using a coaxial transmission line. It consists of two concentric metallic cylinders filled with the test material. Throughout the measurements it was assumed that the medium was a uniform lossless material. The lowest order dispersionless TEM mode propagates along the transmission line.

The waveguide used in the investigation was a standardized coaxial microwave transmission line 23 cm in length (L) and 1.65 cm in diameter (2d). The inner conductor (2a) is 0.160 cm in diameter. The characteristic impedance of a transmission line, defined as the ratio of the voltage between the cylinders and the axial current flowing on one of the conductors at any point, is

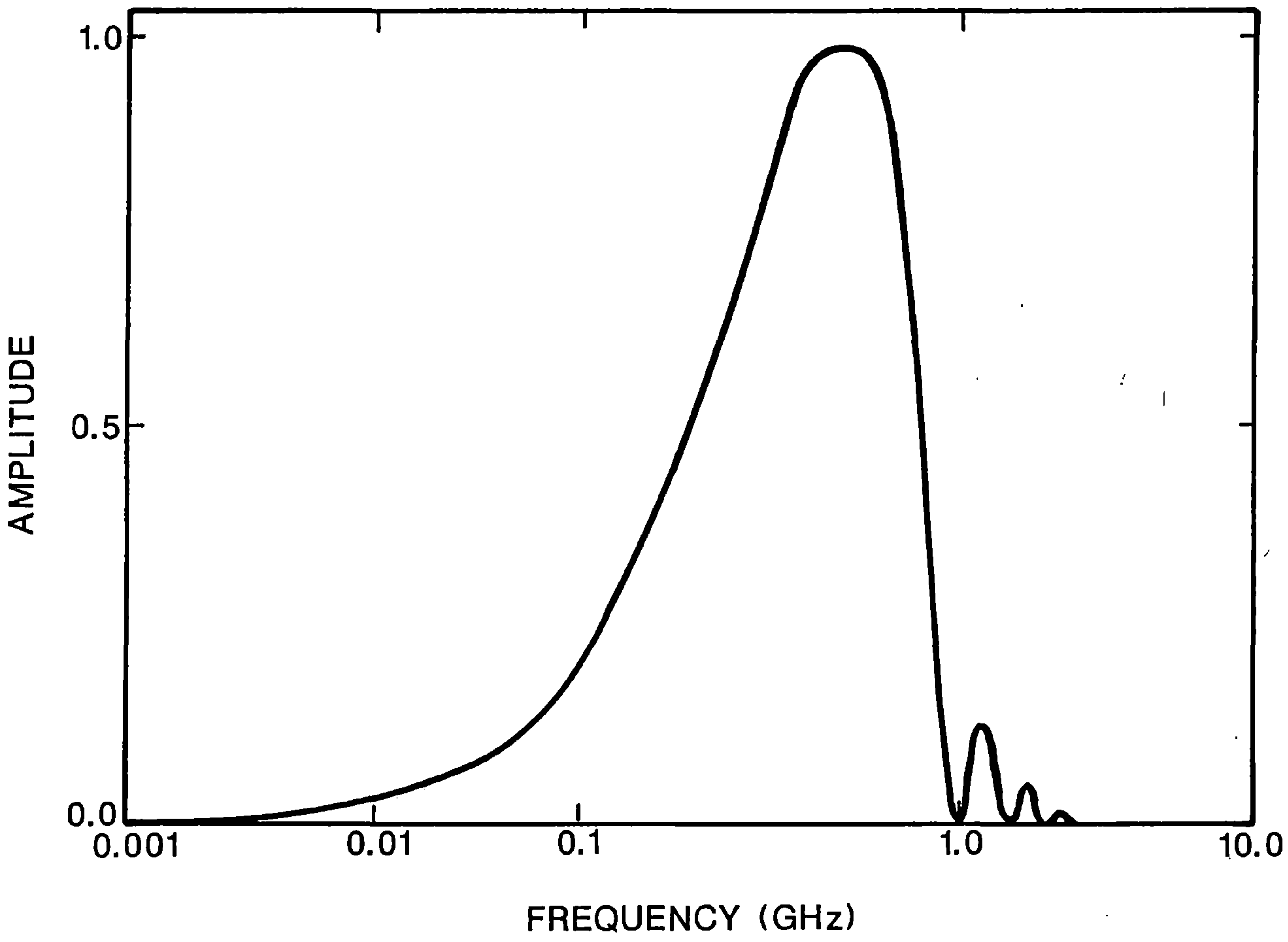


Figure 5. The Fourier Spectrum For a Monocycle Signal For an Arbitrary Amplitude (Lange and Shope, 1981).

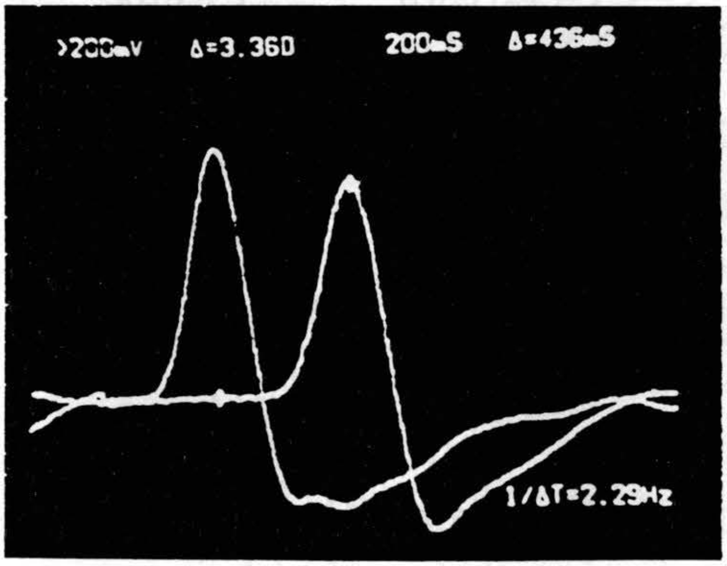


Figure 6. Insertion of the sample in the coaxial line shifts the travel time of the impulse appearing on the oscilloscope. The signals represent air (left) and methanol.

$$Z_o = \frac{60}{\sqrt{\varepsilon}} \ln \frac{d}{a}$$

Where a and d are the inner and outer conductors, respectively. The characteristic impedance, Z_o and the load impedance, Z_L, which is the impedance of the end caps of the coaxial line, affect the electromagnetic wave propagating through the transmission line. The relationship between the reflected and the incident waves is determined by the load and characteristic impedances as

$$P_r = \frac{Z_L - Z_O}{Z_L + Z_O}$$

where P_r is the reflection coeffecient. When the difference between Z_L and Z_O is large, the wave will be mostly reflected, which is not the case of interest. On the other hand, if Z_L and Z_O are equal then the power is fully transmitted. Appendix A provides detailed explanation about the coaxial line and its characteristics.

Oscilloscope and Waveform Digitizer

A D12 dual beam Tektronix oscilloscope was used to display the signal after propagating and passing through the sample. The oscilloscope forms the main frame which hosts a double-wide 5D10 Teletronix waveform digitizer plugged into the unit. The propagating signal was saved in the digitizing oscilloscope to take the measurements and to study its shape compared to the signal passed through an air-filled transmission line. The part which serves this purpose is the waveform digitizer which has the characteristic of displaying and storing the signal. It has two cursors which measure the difference between any two points on the screen. A complete numerical display of cursor measurement values is generated on the oscilloscope screen as shown in Figure 6. The accuracy of the cursor reading was found to be approximately ±4%.

Measurement Procedures

The macroscopic electromagnetic properties of any medium can be described by the complex dielectric constant ε^* and the magnetic permeability μ. The dielectric constant of air or any dry sample is practically real and frequency independent (Shen et al, 1985). The measurements in this work were limited to the real part of the dielectric constant, ε. Physical properties such as ε and μ can be determined from the velocity of propagation of an electromagnetic wave through a coaxial transmission line containing the test material. Using Maxwell's Equations the propagation velocity is given by

$$C = \frac{C_0}{\sqrt{\mu\varepsilon}} \tag{3.1}$$

where $C_0 = 2.988 \times 10^8$ m/sec. is the velocity of propagation in free space. The magnetic permeability of most common materials is close to unity and the variation of this parameter is generally too small to be of much interest (Reitz and Milford, 1967). Considering $\mu = 1$, Equation 3.1 can be written as

$$C = \frac{C_0}{\sqrt{\varepsilon}} \tag{3.2}$$

or

$$\varepsilon = \left(\frac{C_0}{C}\right)^2 \tag{3.3}$$

So, the determination of ε requires the measurement of C. The experimental arrangement in this investigation used the coaxial line to enclose the specimen. The velocity of propagation was determined from the time delay (Δt) of the wave propagating through the line as follows

$$C = \frac{L}{\Delta t} \tag{3.4}$$

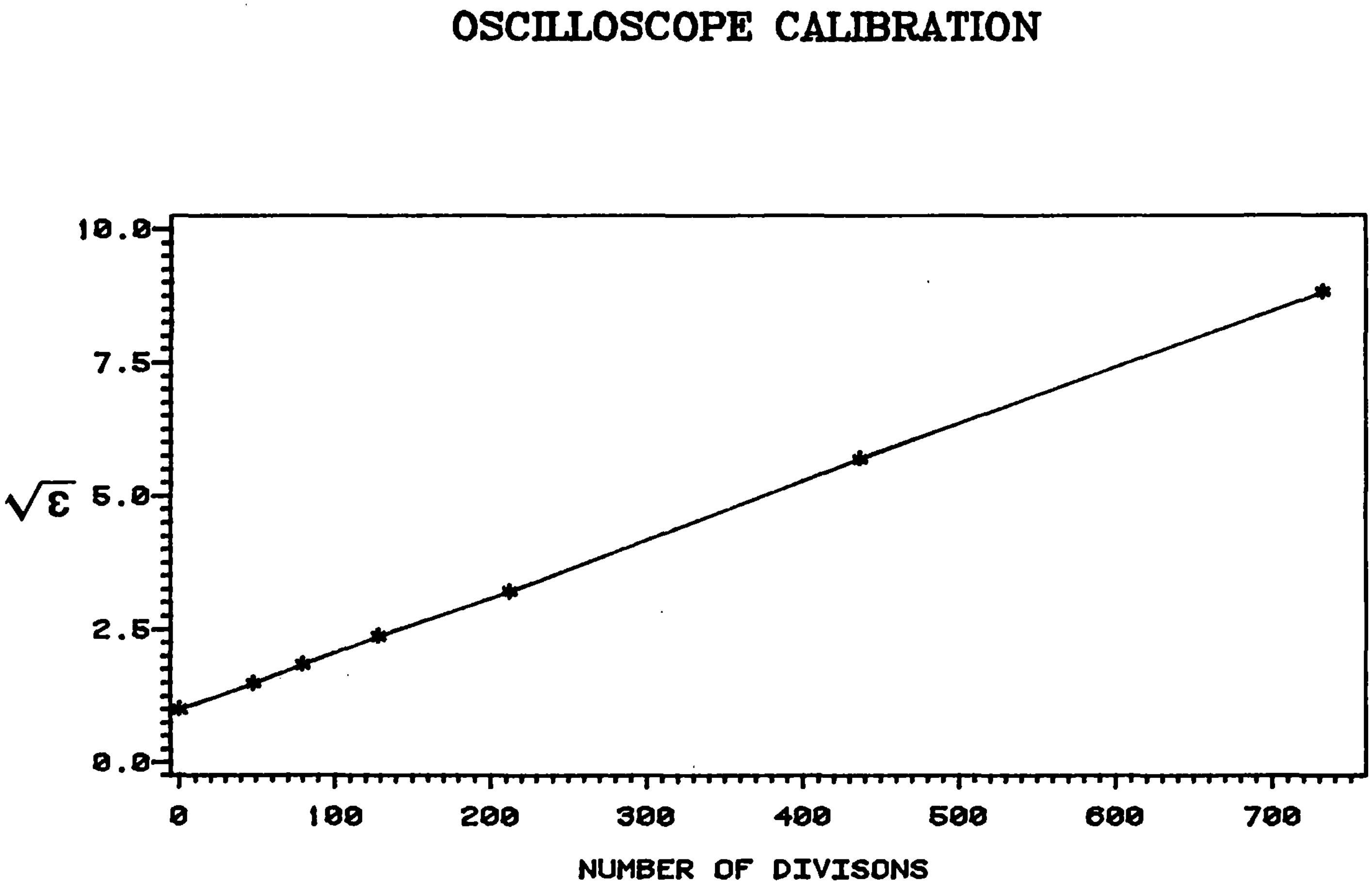


Figure 7. The relationship between the square root of the measured dielectric constant for the reference fluids (Table I) and the impulse position on the oscilloscope screen.

Solving Equation 3.2 and 3.4 results in :

$$\sqrt{\varepsilon} = (C_0/L)\,\Delta t \tag{3.5}$$

As is seen, Equation 3.5 is a linear relationship between the square root of the dielectric constant and the delay time.

Since the quantity of interest is the dielectric constant, an alternative method was developed to directly determine the dielectric constant of the transmission line. This procedure relies on a number of fluids which have well-characterized dielectric properties (Handbook of Chemistry and Physics, 1985). These fluids were referred to as reference fluids (Table I) because they have dielectric constants independent of frequency and test temperature. The oscilloscope screen was calibrated using these fluids to relate the dielectric constant to the position of the signal (Δ) directly. This procedure involves determining the position of the monocycle impulse on the screen relative to a fixed, reference point for each fluid. Figure 6 shows the position of the monocycles for air and another fluid on the oscilloscope screen. The difference between their "peak" positions (Δ) is displayed at the upper right corner of the oscilloscope screen. When the square root of the dielectric constant of the reference fluids was plotted as a funciton of (Δ), the relationship was found to be a straight line represented as

$$\sqrt{\varepsilon} = 1 + m\,\Delta \tag{3.6}$$

where m is the slope of the line and Δ is the difference between the peaks on the screen which represent the position of the signal. When the transmission is air-filled, Δ is zero and ε is 1. Figure 7 shows the relationship expressed by Equation 3.6.

The slope of the line was used to relate the position of the monocycle signal propagating in the transmission line to the dielectric constant of the sample. To ensure that the slope did not vary between measurements, two reference fluids were displayed simultaneously with each measurement. These fluids are methanol and air.

TABLE I

DIELECTRIC CONSTANT OF REFERENCE FLUIDS USED IN THE EXPERIMENT

(Handbook of Chemistry and Physics, 65th Edition, P. E-50)

Fluid	Dielectric Constant
Air	1.0
Cyclohexane	2.02
Carbontetrachloride	2.238
Trichloroethylene	3.4
Chlorobenzene	5.62
1,2 Dichloroethane	10.36
Acetone	21.5
Methanol	32.63
Water	78.54

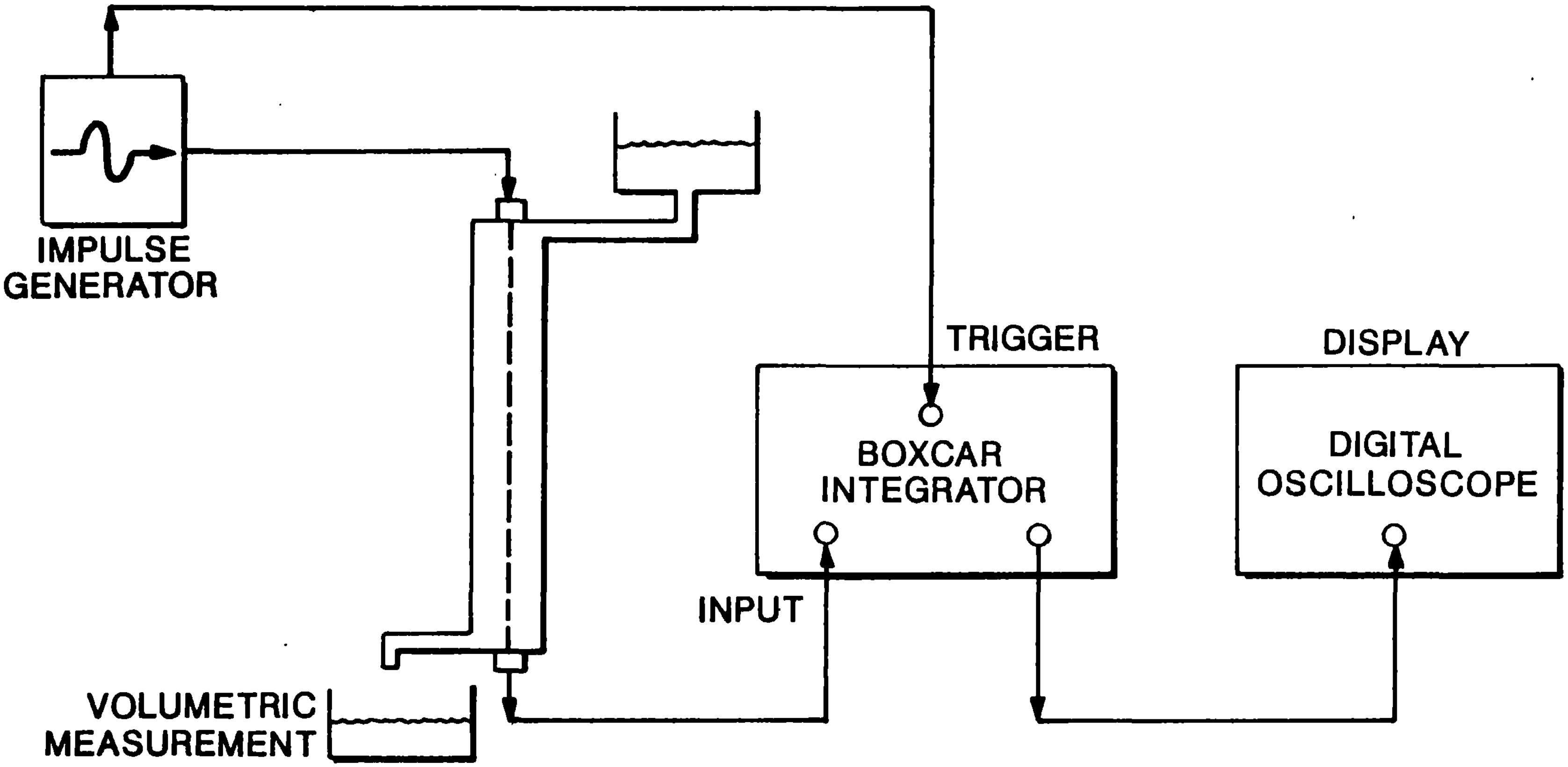


Figure 8. The experimental apparatus is modified to be used in monitoring the flow of fluids through porous media contained in the transmission line.

Flow of Fluids Arrangements

The Experimental set up was modified so that the dielectric measurements could be used to study the properties of fluid flow and storage capacity of porous media. The procedure involved the saturation of the porous medium with a certain fluid. A second fluid was introduced to the system, and the flow of the two fluids was monitored using the dielectric measurements. The volume of the discharged fluid was measured both volumetrically and by using the dielectic constant. The combination of the flowing fluids included systems which contained two, three, or four different flowing fluids. Table III is a summary of the different saturated porous media and the fluid combinations used in the flow measurements. The experimental arrangement for the fluid flow is shown in Figure 8.

Preparation of Materials

A wide range of materials with different physical and geological properties taken from different sources (Table II) have been used in this study. Some of these materials whose dielectric constant values are known are used as standards. The standard materials included a glass matrix obtained from the National Bureau of Standards (NBS) (U.S. Department of Commerce), and dielectric rods supplied by Emerson and Cuming, Inc. Non-standard materials included uniform sand and common earth formations such as sandstone, limestone and loamy to clayey soils. Both standards and non-standards have been tested in their consolidated and unconsolidated states.

TABLE II

PROPERTIES OF DIELECTRIC MEDIA USED IN THE MEASUREMENTS

Material	Particle Shape	Particle Size (mm)	Solid Dielectric constant	Porosity ϕ (%)
NBS glass matrix	nonuniform	0.075 - 1.0	7.45	40
Ottawa Sand	Uniform	.45	3.89	33
Glass Beads	Spherical, Uniform	.1, .5, 1, 3, 6 (independently)	6.15 (average)	36 - 37
Sandstone	Irregular nonuniform	0.150 - .600	4.62	41
Limestone	Irregular nonuniform	0.150 - .600	7.24	33
Seminole Loam Soil	Irregular nonuniform	.063 - .600	4.56	43
Grain-Lucien Complex Soil	Irregular	0.063 - .600	5.48	48

TABLE III

THE COMBINATION OF FLUID FLOW THROUGH POROUS MEDIA THE POROUS MEDIA WAS THE OTTAWA SAND

System #	Figure #	Fluid of Initial Saturation	Combination of Fluid Flow			
			A	B	C	D
I	46	Water	Carbon-tetrachloride	Water		
II	47	Carbon-tetrachloride	Water	Methanol	Water	
III	48	Water	Crude oil	Water		
IV	49	Crude oil	Water	Methanol	Water	
V	50	Crude oil	Water	Cyclohexane	Water	
VI	51	Crude oil	Water	Cyclohexane	Methanol	Water
VII	52	Crude Oil Water	Surfactant	Cyclohexane Water	Surfactant	
VIII	53	Crude oil Water	Surfactant	Cyclohexane	Methanol	Water

Standard Materials

For dielectric measurement calibration, the NBS glass matrix with a dielectric constant of 7.45 ± .05 was used. This glass is used to establish the experimental procedure used to determine the dielectric constant of other materials. It is supplied in the form of a block 5 cm square by 2.5 cm thick which was crushed to small non-uniform particles before use.

Dielectric rods were obtained from a second source (Emerson and Cuming, Inc.) at seven different values of the dielectric constant, namely 2.55, 10.0, 12.0, 16.0, 20.0, 25.0, and 30.0. The uncertainity of these values as dictated by the supplier was ± 3% for the dielectric constant less than 16.0 and ±10% for the others. The dielectric constant of these rods have an extremely low dependency on moisture and/or temperature. The rods were machined into circular cylinders with circular concentric holes drilled to fit the coaxial transmission line and imitate the geometry of the actual oil well cores.

Non-standard Materials

Consolidated as well as unconsolidated materials of known dielectric constant were investigated. The unconsolidated samples included uniform sand, glass beads, limestone, sandstone and soils. The consolidated samples were three types of sandstone cores of different geological properties.

The uniform sand was the Ottawa sand supplied by Fisher Scientific Company as non-spherical particles. In constrast, the glass beads, are smooth spherical particles and were supplied by Sargent-Welch Scientific Company. The sizes of glass beads used in the measurements ranged between .1 mm and 6 mm in diameter (Table II). Sandstone and limestone were ground into particles which were passed through two standard sieves No. 100 and No. 30 (USA standard testing sieves, Sargent-Welch Scientific Company) which correspond to sizes between .150 and .600 mm. Table (II) gives detailed information about the materials. Particles passed through sieve No. 30 which were retained on sieve

No. 100 were collected and used for experimentation. Different soil samples (Seminole loam, Grainola-Lucion complex, Bates and Bowie) collected from various geological regions were used in this study. The characteristics of these soils are quoted from the description of the soil bulletin provided by the United States Department of Agriculture (USDA) of Stillwater, Oklahoma. Seminole loam is a prairie soil susceptable to water erosion. It is moderately well drained and absorbs water slowly. The Grainola-Lucien complex soil is sandy prairie consisting of a mixture of deep Grainola and shallow Lucien soils that were well drained and subject to water erosion. Bates and Bowie are mainly clayey soils so only one sieve (No. 100) was used and particles which passed through that sieve were collected and used.

The nonstandard consolidated materials were represented by three sandstone cores which were cut to fit the transmission line.

Preparation of Emulsions and Solutions

There are many ways of producing an emulsion from two fluid phases that are mutually not or only slightly soluble. It is usually achieved by applying mechanical energy which falls into the three broad categories of mixing, colloid milling, and homogenizing. The mixing method was used, in which the desired amounts of fluids were put into an electrical blender. First the interface between the phases was deformed to such an extent that large droplets form, which are broken up or disrupted into smaller ones. It was found that intermittent mixing with rest periods between mixings was vastly more effective than uninterrupted mixing (Gopal, 1968). In the preparation of emulsions used in this investigation three mixing periods were applied with 30-40 seconds rest in between.

Solution preparations were easier and straightforward with the two fluids being mixed until a homogeneous mixture was obtained.

Accuracy of the Measured Parameters for Porous Media

The calculation of the effective dielectric constant requires the knowledge of some parameters which can be experimentally determined in the laboratory. These parameters include the porosity of the sample under consideration (ϕ), its dielectric constant (ε_s), water saturation (S_w), and water content (θ_w).

The porosity is the ratio of the total pore volume (V_p) to the total volume (V_T) of the medium. If the sample is unconsolidated the total volume of the medium is practically the volume of the transmission line containing the sample. The pore volume V_p is determined by the amount of fluid used to fully saturate the medium. On the other hand, if the material is consolidated the total volume (V_T) is the volume of the rock itself regardless of the volume of coaxial line.

To determine the porosity of unconsolidated medium, the coaxial line was filled first with a predetermined volume of dry sample then was fully saturated with water. Filling the coaxial line is a very critical step in determining the porosity which, in turn, is used to calculate the solid dielectric consant. In fact, packing the unconsolidated material could be achieved either by filling the coaxial line with the material without shaking or hitting the coaxial line or by gradually introducing small amounts of the material at a time while hitting the coaxial line from its side. The latter procedure was chosen because it proved to be more reproducible in defining the amount of solid media filling the coaxial line. After packing the coaxial line the dielectric constant of the dry sample was measured.

The porosity was determined by saturating the porous material with water whose volume was determined from the difference in the weights between the dry and the saturated materials. The volume of water in the system was determined using a pipet whose graduation has ± .05 ml limit of accuracy. The amount of water could be determined within a range of precision ± .25 ml making the overall accuracy of porosity determination .005. The water saturation (S_w) is the ratio of the volume of water in the system (V_w) to the pore volume (V_P). The water content (θ_w) is defined as the ratio of a volume of water (V_w) in a pore to the total volume (V_T) of the pore, regardless of the porosity of the medium. In principle $\theta_w = S_w\phi = (V_w/V_P)(V_P/V_T) = V_w/V_T$.

For consolidated materials, determination of the volumetric parameters is rather different. Samples were first thoroughly dried using aspiration and heating techniques. The sample was subjected to the drying process until its weight became constant in time. To determine the core porosity, a known weight of the dry sample core was put in an aspirator containing water until it reached its full saturation and this was indicated by the cessation of air bubbling from its surface. The difference in the weight between the dry sample and its weight after being fully saturated was calculated and considered as the pore volume. The total volume (V_T) of the consolidated materials is the net volume of the sample excluding the volume of the central hole needed to fit in the coaxial sample holder. The water saturation and water content were determined in the following way:

1. The sample was fully saturated with known amounts of water, (V_P).
2. It was weighed along with the coaxial line and dried in the oven for 4-6 hours at 105° - 110° C.
3. The coaxial line (including the sample) was weighed and the difference gave the amount of water which evaporated from the sample.
4. The amount of water left inside the sample (V_w) determined the water saturation and water content.

CHAPTER IV

THEORETICAL BACKGROUND

The dielectric constant is a measure of the extent to which the electric charge distribution in the material can be distorted or polarized by the application of an electric field. The first section deals with the microscopic and macroscopic responses of a material when subjected to an electric field. The relationship between macroscopic parameter (susceptibility) and microscopic parameter (polarizability) and their relation to the dielectric constant are discussed.

The mixture formulas, which relate the dielectric constant of a composite material to those of its components, are presented in the second section. There are a large number of such formulas, but emphasis is placed on the ones which have wide field and industrial applications, such as Effective Medium Theory (EMT), Square Root Equation (SRE) and Three Quarter Equation (TQE). Since the most common mixing laws in the field are EMT and SRE, a detailed derivation of both are included. The theoretical calculation of the dielectric constant for both fully and partially saturated materials are also discussed. The third section deals with the theory of emulsions.

Finally, when the material under investigation is consolidated such as oil well cores, there is always a need for a correction formula to extract the dielectric constant of the sample from the measurement of the coaxial line. This correction formula and the parameters which affect it are discussed in the last section.

Derivations and Relationships

When an electrtic field $\mathbf{E}_0$ is applied to a dielectric medium, the medium will respond on two scales: macroscopic and microscopic (molecular). The macroscopic properties are the electrical susceptibility and dielectric constant, while the microscopic characterize the molecular polarizability. The charges bound in each molecule of the medium respond to the applied field and execute perturbation motions. This corresponds to the generation of electric dipole moments, which in turn, contributes to the total internal field. The resultant dipole moment per unit volume is called the electric polarization **P**. The total field **E** is called the macroscopic electric field and is the average electric field in a small region of the dielectric which contains a large number of molecules. Generally, the polarization **P** depends on the electric field **E**. This dependence can take several forms. If the dielectric medium is linear and isotropic, the induced polarization **P** is parallel to **E** with a coefficient of proportionality that is independent of direction.

$$\mathbf{P} = \chi \mathbf{E}. \tag{4.1}$$

The constant χ is called dielectric susceptibility of the medium. For non-isotropic dielectrics the scalar χ must be replaced by a tensor of the second rank. On the other hand, if the field intensities are very high, the proportionality no longer holds and correction term proportional to E must be added. The most common relationship between **P** and **E** is given by expression 4.1 which is known as the macroscopic relationship.

The polarization **P** will induce a depolarization field $\mathbf{E}_1$ which tends to oppose E_0 (Jackson, 1972). The macroscopic field is the resultant of both $\mathbf{E}_0$ and $\mathbf{E}_1$. The depolarization field, $\mathbf{E}_1$, is proportional to **P** such that

$$\mathbf{E}_1 = -\mathrm{A}\mathbf{P} \tag{4.2}$$

where A is called the depolarization factor. If $\mathbf{P}_a$, $\mathbf{P}_b$ and $\mathbf{P}_c$ are the components of the polarization P (a, b and c refer to the principal axes of an ellipsoid) then the components of the depolarization field can take the form of

$$\mathbf{E}_{1a} = -A_a\mathbf{P}_a \qquad \mathbf{E}_{1b} = -A_b\mathbf{P}_b \qquad \mathbf{E}_{1c} = -A_c\mathbf{P}_c$$

where A_a, A_b and A_c are the depolarization factors which their values depend on the ratio of their principal axes (**E** of 4.41). $A_a + A_b + A_c = 4\pi$ in CGS and 1 in SI. If the applied field $\mathbf{E}_o$ is uniform and parallel to a principal axis of the ellipsoid, then

$$\begin{aligned} \mathbf{E} &= \mathbf{E}_o + \mathbf{E}_1 \\ &= \mathbf{E}_o - A\mathbf{P} \end{aligned} \tag{4.3}$$

substituting Equation 4.1 for **E** leads to

$$\mathbf{P} = \frac{\chi}{1 + A\chi} \mathbf{E}_o \tag{4.4}$$

This equation gives the relation between the external field and the polarization when A and χ are known.

The microscopic relationship is defined as the relation between average dipole moments of the molecule, $\mathbf{p}_m$, which will be induced in the medium, and the molecular field $\mathbf{E}_m$ in the following form

$$\mathbf{p}_m = \alpha\mathbf{E}_m \tag{4.5}$$

where α is called the molecular polarizability or polarizability. The field $\mathbf{E}_m$ in Equation 4.5 is assumed to be constant and it is the field due to all external sources except the element itself; the field which the element itself produces does not act to polarize it.

$\mathbf{E}_m$ needs not to be the same as the macroscopic field. In rarefied media where molecular separations are large, there is little difference between the macroscopic field and that acting on any molecule or group of molecules (Jackson, 1972). But in dense media with closely packed molecules the polarization of the neighborhood gives rise to an internal field $\mathbf{E}_i$ at any given molecule, in addition to the applied field $\mathbf{E}$ so that the molecule field became

$$\mathbf{E}_m = \mathbf{E}_o + \mathbf{E}_i \tag{4.6}$$

On the other hand, the internal field could be divided into near and distant fields. The distant ones are E_1 and the Lorentz field, E_L. The field $\mathbf{E}_m$ at the latice point is the sum of the applied field, $\mathbf{E}_o$, and the induced fields;

$$\mathbf{E}_m = \mathbf{E}_o + \underbrace{\mathbf{E}_1 + \mathbf{E}_L}_{\text{Distant}} + \underbrace{\mathbf{E}_n}_{\text{Near}} \tag{4.7}$$

$$= \mathbf{E} + \mathbf{E}_L + \mathbf{E}_n \tag{4.8}$$

where $\mathbf{E}_n$ is the near field, $\mathbf{E}_L$ is the Lorentz field, and $\mathbf{E} = \mathbf{E}_o + \mathbf{E}_1$ is the macroscopic field. The near field $\mathbf{E}_n$ of cubically symmetric dipole array vanishes due to the symmetry. If $\mathbf{E}_n = 0$ for a highly symmetric situation, then $\mathbf{E}_n = 0$ also for completely random situations (Jackson, 1972). The Lorentz field, $\mathbf{E}_L$, is calculated to be $4/3\pi\mathbf{P}$ (Kittle, 1973). Thus Equation 4.5 can be written as

$$\mathbf{p}_m = \alpha\mathbf{E}_m = \alpha(\mathbf{E} + 4\pi/3\,\mathbf{P}) \tag{4.9}$$

Since $\mathbf{P} = N\mathbf{p}_m$ where N is the number of mulecules per unit volume, then

$$\mathbf{P} = N\alpha(\mathbf{E} + 4\pi/3\,\mathbf{P}) \tag{4.10}$$

Substituting for **E** in terms of **P** (from Equation 4.1) defines the susceptibility of a substance as

$$\chi = \frac{N\alpha}{1 - 4/3\,\pi N\alpha} \qquad (4.11)$$

This is a form of relationship between the macroscopic property (χ) and microscopic property (α) of a dielectric. The relationship between the dielectric constant ε and the electric susceptibility χ is deduced from the definition of the displacement current **D** (Bottcher, 1973). **D** is defined as

$$\mathbf{D} = \mathbf{E} + 4\pi\mathbf{P} \qquad (4.12)$$

Using Equation 4.1 for **P** yeilds,

$$\begin{aligned}\mathbf{D} &= (1 + 4\pi\chi)\mathbf{E} \\ &= \varepsilon\mathbf{E} \qquad (4.13)\end{aligned}$$

where ε is the dielectric constant of the medium and is expressed as $\varepsilon = 1 + 4\pi\chi$. It is defined as the measure of the extent to which the electric charge distribution in the material can be distorted or polarized by the application of the electric field. In an anisotropic material the dielectric constant is a second-rank tensor denoded by ε_{ij} and Equation (4.13) is expressed as

$$\begin{aligned}D_x &= \varepsilon_{11}E_x + \varepsilon_{12}E_y + \varepsilon_{13}E_z \qquad (4.14)\\ D_y &= \varepsilon_{21}E_x + \varepsilon_{22}E_y + \varepsilon_{23}E_z \\ D_z &= \varepsilon_{31}E_x + \varepsilon_{32}E_y + \varepsilon_{33}E_z\end{aligned}$$

Therefore, the relation between macroscopic parameter (dielctric constant) and microscopic parameter (molecular polarizability) can be written as

$$\begin{aligned}\varepsilon &= 1 + 4\pi\chi \\ &= 1 + 4\pi \frac{\alpha}{1 - 4\pi/3\,N\alpha}\end{aligned}$$

or $$\alpha = \frac{3}{4\pi N}\,\frac{(\varepsilon - 1)}{(\varepsilon + 2)} \qquad (4.15)$$

which is known as the Clausius-Mossitti equation, generally referred to as CM Equation. At optical frequencies, $\varepsilon = n^2$, then Equation 4.15 is called the Lorentz-Lorenz equation.

Dielectric Constant and Polarizability

Application of an external electric field to any substance causes a local shift of the centers of positive and negative charge (electrons and atoms). Since the moving units are very small, the response to application of the field is practically instantaneous. Some substances display ionic and electronic polarization only. The ionic contribution comes from the displacement of a charged ion with respect to other ions. The electronic contribution arises from the displacement of the electron shell relative to a nucleus. When the external field alternates at extremely high frequencies this polarization gets insufficient time to establish itself, and the refractive index approaches that of a vacuum. Some substances, such as water, have an additional mechanism of polarization. The molecules of these substances possess a natural permanent dipole moment, due to the asymmetry of their electrical charge distribution. Upon the application of a field, a degree of molecular orientation takes place that creates some order among the originally randomly oriented molecular dipoles. In this way, an overall orientation in the field direction results, the so called orientational polarizaton. If the substance is heterogeneous, and has any conductivity, this will mainly determine its dielectric behavior at low frequencies, but its influence will decline rapidly at higher frequencies. It is called an interfacial polarization which arises from the accumulation of charge at structural interfaces. The dielectric constant of a material could be affected by four parts of the polarization, interfacial, ionic, atomic and dipolar. The separate contributions as a function of frequencies are indicated in Figure 9.

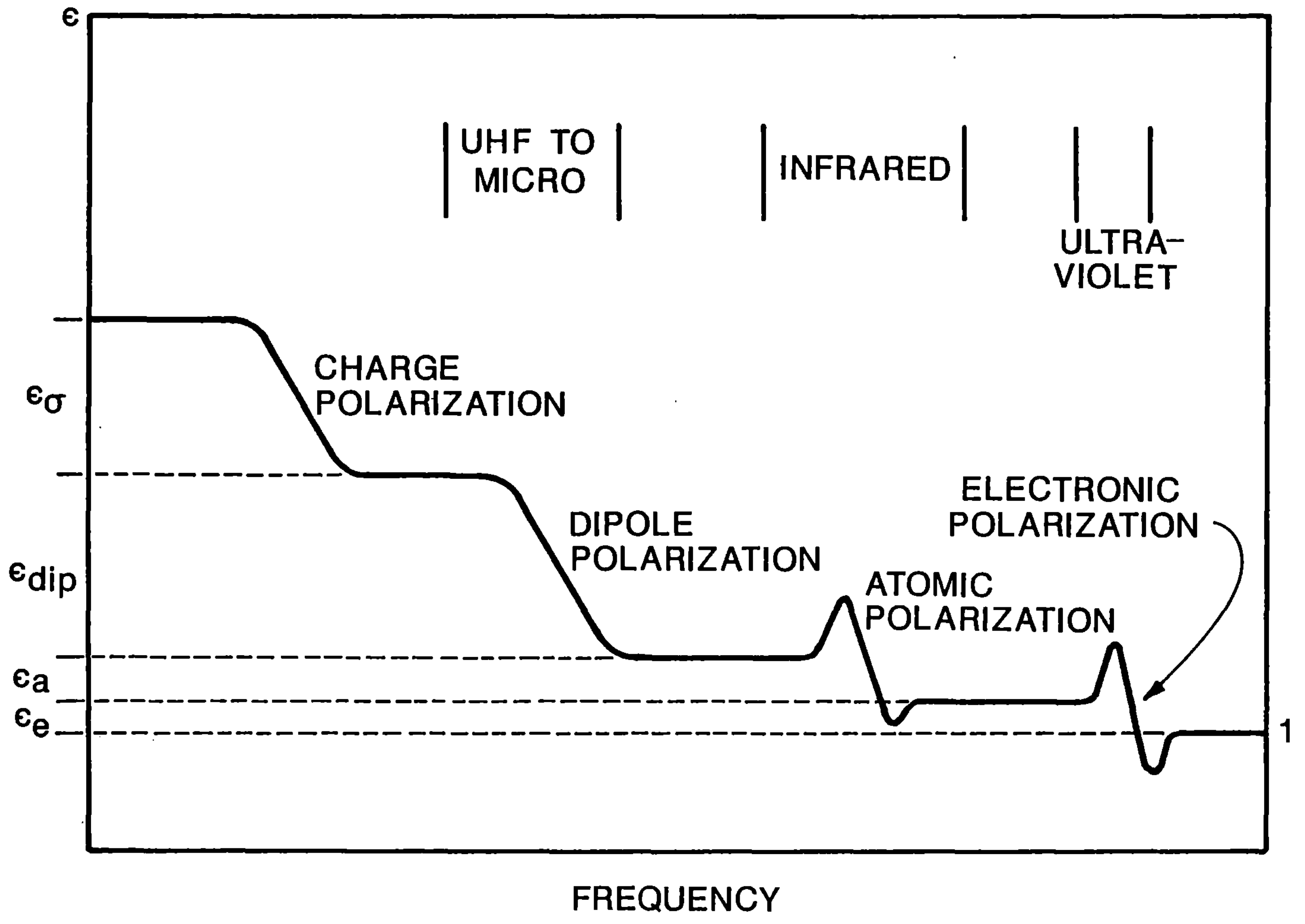


Figure 9. The Frequency Dependence of the Dielectric Constant on the Several Contributions to the Polarizations (Kittle, 1973).

Composite Dielectric Constant and Mixing Law

Expressions for dielectric constant of heterogeneous mixtures have been proposed since the beginning of the nineteenth century. Many theoretical works have attempted to predict an overall effective dielectric constant for a composite system in terms of those of its constituents' phases and their compositions.

When a fluid of dielectric constant ε_f and a solid dielctric constant ε_s mix to compose a system, the resultant component will have a dielectric constant ε. The relation between ε_s, ε_f and ε depends on the volumes of the components that constitute the system. This relationship has been refered to as mixing laws or mixture formulas. Generally they can be formulated as

$$f(\varepsilon) = \Sigma f(\varepsilon_i)\phi_i \qquad i = s, f \tag{4.16}$$

where ϕ_i is the volume fraction for the component i and f is a function that governs the relationship. Generally, the form of the mixing laws vary considerably, depending upon whether its origin has a basic physical derivation or it is an empirical formulation. Present discussion is limited to the most common expressions, while a broader coverage of mixing laws is presented in the literature (Tigna, et al. 1973).

Lichtencker and Rother Formula

A general empirical formula which can take more than one specific form was suggested by Lichtencker and Rother (1937) as:

$$\varepsilon = [\, \phi\varepsilon_f^c + (1-\phi)\, \varepsilon_s^c]^{1/c} \tag{4.17}$$

The exponent c is determined empirically. Various mixing laws could be derived from Equation 4.17, depending on the value given to the exponent c. For a three-component mixture (e.g. water, fluid and solid) (Meador and Cox, 1975), Equation 4.17 can be written as

$$\varepsilon = [S_w \phi \varepsilon_w{}^c + (1 - S_w)\,\phi \varepsilon_f{}^c + (1 - \phi)\,\varepsilon_s{}^c\,]^{1/c} \tag{4.18}$$

where S_w is the water saturation of the medium.

Time of propagation Method (TPO)

TPO relates the traveltime of the signal through the medium to the real part of the dielectric constant. For a plane wave traveling in the z direction, the solution for the wave equation (Freedman et al., 1979) is

$$\mathbf{E} = \mathbf{E}_0\, e^{i(kz-\omega t)} \tag{4.19}$$

where $\mathbf{E}_0$ is the magnitude of the electric field associated with the wave, ω is the angular frequency of the EM wave, t is the time it takes to travel a distance z and k is the complex wave number. From the solutions of Maxwell Equations and using Equation 4.23, the propagation constant can be equated to an expression governing the phase shift and the attenuation of the wave per unit length.

$$k = \omega(\mu\varepsilon^*)^{1/2} = \beta + i\alpha \tag{4.20}$$

where ε^* is the complex dielectric constant ($\varepsilon^* = \varepsilon' + i\varepsilon''$) and μ is the magnetic pereability, α is the attenuation of the amplitude of the wave, which is the decrease in the amplitude with distance, and β is the phase shift in radians per meter. Substituting Equation 4.20 into 4.19, the focus of constant phase front can be determined from

$$\beta z - \omega t = \text{constant} \tag{4.21}$$

Differentiating Equation 4.21 with respect to time yields the phase velocity of the plane wave,

$$\frac{dz}{dt} = V_P = \frac{L}{t_{Pl}} = \frac{\omega}{\beta} \tag{4.22}$$

V_P is the velocity of propagation, which is the speed at which a signal is transmitted along a transmission line, and t_{Pl} is the propagation time of the wave, which is the time the phase front of the wave takes to advance one meter. t_{Pl} is related to other parameters by taking the square of Equation 4.20 and equating the respective real and imaginary parts on both sides resulting the following equations,

$$\beta^2 - \alpha^2 = \omega^2\mu\,\varepsilon' \tag{4.23}$$

and $$2\alpha\beta = \omega^2\mu\varepsilon'' \tag{4.24}$$

Dealing with the real part of dielectric constant, ε', and substituting (4.22) into (4.23) leads to

$$\mu\varepsilon' \equiv (t^2_{pl} - \alpha^2/\omega^2) \tag{4.25}$$

Since μ is almost unity for all media of our interest, Equation (4.25) can be written as

$$\varepsilon' = t^2_{po} = (t^2_{pl} - \alpha^2/\omega^2) \tag{4.26}$$

The physical meaning of t_{Po} is that it is the propagation time of a time-harmonic electromagnetic wave in a fictitious medium characterized by μ=1 and dielectric constant of ε', with ε" set equal to zero. This medium is lossless because its dielectric constant is a real number, herein written as ε.

Having defined the quantity t_{po}, the TPO formula for a two-component is written as

$$t_{po} = \phi\, t_{pf} + (1 - \phi)\, t_{ps} \tag{4.27}$$

For a three-component system (including air, water and solid) the TPO model is

$$t_{po} = S_w\phi t_{pw} + (1 - S_w)\phi\, t_{pa} + (1 - \phi)\, t_{ps} \tag{4.28}$$

in which t_{px} is proportional $\sqrt{\varepsilon_x}$ where x refers to the components w, s, and a. ε_x is the real part of dielectric constant for the component x and S_w is the water saturation, then

$$\sqrt{\varepsilon} = S_w\phi\sqrt{\varepsilon_w} + (1 - S_w)\,\phi\,\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s} \tag{4.29}$$

In brief TPO says that the square root of the real part of the dielectric constant is equal to the volumetric sum of those of its components. For multiple mixture,

$$\sqrt{\varepsilon} = \Sigma \phi_i \sqrt{\varepsilon_i} \tag{4.30}$$

Complex Refractive Index Method (CRIM)

This is an empirical relationship which has been derived independently by many observers (Birchak et al., 1974; Sen et al., 1981; and Rau and Wharton, 1982). The form of CRIM is identical to that of TOP with the exception that CRIM uses the complex dielectric constant instead of its real part. A phenomological derivation of CRIM assumes that the wave is traveling through a series of parallel layers which represent varying geological materials. The layers thicknesses are much greater than a wavelength. The net traveltime, T, of the wave is the sum of the traveltimes in each layer

$$T = \Sigma t_i = \Sigma\, l_i/c_i \tag{4.31}$$

where l_i is the thickness of the i^{th} layer and c_i is its propagation velocity. For a two layer of total thickness L, the traveltime is

$$\begin{aligned} T &= t_1 + t_2 \\ &= \frac{l_1}{c_1} + \frac{l_2}{c_2} = \frac{L}{c'} \end{aligned} \tag{4.32}$$

where c' is the "composite" velocity of the two layers and $L = l_1 + l_2$. Assuming the layers have the same area A and the percentage of each component in the system is $l_{1/L}$ and $l_{2/L}$. If $l_{1/L}$ is associated with pure fluid and $l_{2/L}$ with solid matrix, then from Equation 4.32

$$\frac{L}{C_o} \sqrt{\varepsilon^*} = \frac{\phi L}{C_o} \sqrt{\varepsilon^*_f} + \frac{(1-\phi)L}{C_o} \sqrt{\varepsilon^*_s}$$

or

$$\sqrt{\varepsilon^*} = \phi\sqrt{\varepsilon^*_f} + (1 - \phi) \sqrt{\varepsilon^*_s} \tag{4.33}$$

And for three component material

$$\sqrt{\varepsilon^*} = S_w\phi\sqrt{\varepsilon^*_w} + (1-S_w)\phi\sqrt{\varepsilon^*_a} + (1-\phi)\sqrt{\varepsilon^*_s} \tag{4.34}$$

Equation (4.34) is similar to Equation (4.29) with ε^* replaced by ε. For multilayers of N sheets

$$\sqrt{\varepsilon^*} = \Sigma\ \phi_i\sqrt{\varepsilon^*_i}\ . \tag{4.35}$$

Generally speaking, ε^*_a and ε^*_s are equal to ε_a and ε_s because they have only real part for their dielectric constant (Shen et al., 1985). Ultimately, the difference between CRIM and TPO will not be very large. Both formulas can be derived from Lichtencker and Rother Equation by putting the exponent equal 0.5 with respective real or imaginary dielectric constant. Therefore, it is called the Square Root Equation (SRE).

Effective Medium Theory (EMT)

The derivation of the form of EMT is based on the theory of disordered systems in solid state physics (Hasted, 1973). The EMT is derived for a two-component system consisting of a fluid and a solid of dielectric constants ε_f and ε_s with porosities ϕ and $(1-\phi)$, respectively.

The following discussions deal with the derivation of this theory for general ellipsoidal particles of dielectric constants ε_s dispersed in a fluid of dielectric constant ε_f. Let the axes of the ellipsoidal particle be a, b, and c. When a homogeneous external field $\mathbf{E}_0$ is applied along the a-axis, the field within the ellipsoid, $\mathbf{E}_a$, is uniform (Bottcher, 1973) and given by

$$\mathbf{E}_a = \frac{\varepsilon_f \mathbf{E}_0}{\varepsilon_f + A_a(\varepsilon_s - \varepsilon_f)} \tag{4.36}$$

where A_a is the depolarizaiton factor along the a-axis, and is given by

$$A_a = \frac{abc}{2}\int_0^\infty \frac{ds}{(s+a^2)\,[(s+a^2)(s+b^2)(s+c^2)]^{1/2}} \tag{4.37}$$

with $A_a + A_b + A_c = 4\pi$ in CGS and 1 in SI. The induced polarization per unit volume is related to $\mathbf{E}_a$ as follows:

$$\mathbf{P}_a = \frac{(\varepsilon_s - \varepsilon_f)}{4\pi} \mathbf{E}_a \tag{4.38}$$

and the induced dipole moment $\mathbf{p}_a$ is

$$\mathbf{p}_a = 4/3\ \pi abc\ \mathbf{P}_a \tag{4.39}$$

With the definition of polarizability from Equation 4.5 and Equation 4.39;

$$\alpha_a = abc \frac{\varepsilon_f(\varepsilon_s - \varepsilon_f)}{3[\varepsilon_f + A_a(\varepsilon_s - \varepsilon_f)]} \tag{4.40}$$

If a molecule with permanent dipole moment is surrounded by other particles, the field of the permanent dipole polarizes its environment, and the resulting inhomogeneous polarization of the environment will give rise to a field at the dipole which is called the reaction field $\mathbf{E}_R$. The induced dipoles polarizes the immediate area surrounding a particle. The average field (Hasted; 1973) can then be modified to

$$<\mathbf{E}> = \frac{<\mathbf{E}_a>}{(1 - \alpha_a E_R)} \tag{4.41}$$

When the particle is introduced to the medium, the dielectric constant of the medium surrounding the particle is not necessarily equal to ε_f, but has a different value which is denoted as ε_f'. Thus Equation 4.36 becomes,

$$<\mathbf{E}_a> = \frac{\varepsilon_f' \mathbf{E}_o}{[\varepsilon_f' + A_a (\varepsilon_s - \varepsilon_f')]} \tag{4.42}$$

and using (4.38), (4.39) and (4.42) the induced dipole moment is

$$\mathbf{p}_a = abc \frac{(\varepsilon_s - \varepsilon_f)\ \varepsilon_f'\ \mathbf{E}_o}{3[\varepsilon_f' + A_a(\varepsilon_s - \varepsilon_f')]} \tag{4.43}$$

If ε_s is eliminated from the previous equation, then

$$p_a = \frac{\varepsilon'\alpha_a \qquad \varepsilon_f \quad E_0}{[\varepsilon_f' + A_a(\varepsilon_f - \varepsilon_f')] \quad \varepsilon_f - \dfrac{\alpha_a A_a(1-A_a)(\varepsilon_f' - \varepsilon_s)}{abc\,[\varepsilon_f' + A_a(\varepsilon_f - \varepsilon_f')]}} \tag{4.44}$$

Using Equations (4.41) to (4.43) the expression of the reaction field can be found as

$$E_R = \frac{3 \qquad A_a(1-A_a)(\varepsilon_f' - \varepsilon_f)}{abc \qquad \varepsilon_f[\varepsilon_f' + A_a(\varepsilon'_f - \varepsilon_f)]} \tag{4.45}$$

The average change in polarizaton per unit volume owing to the introduction of the ellipsoid ε_s into the medium is $<P>$, which can be expressed as

$$<P> = N<p> = N\alpha<E> \tag{4.46}$$

Where N is the number of ellispoids per unit volume, and $<E>$ is the average field throughout the mixture whose dielectric constant ε is related to P as

$$<P> = (\varepsilon - \varepsilon_f)E \tag{4.47}$$

If the volumes of fluids and solid are V_f and V_s respectively, and the total volume $V = V_s + V_f$, then $\phi = V_f/V$ and $(1-\phi) = V_s/V$. The solid volume fraction is

$$(1 - \phi) = {}^{4}/{3}\pi abcN, \tag{4.48}$$

thus from the last three equations,

$$(\varepsilon - \varepsilon_f)<E> = N\alpha_a<E>$$

$$(\varepsilon - \varepsilon_f) = \frac{(1 - \phi)}{(4\pi/3)\,abc}\,\alpha_a \tag{4.49}$$

Substituting for the polarizability from (4.40), then Equation 4.49 becomes

$$(\varepsilon - \varepsilon_f) = \frac{(1 - \phi)\,(\varepsilon_s - \varepsilon_f)\,\varepsilon_f'}{[\varepsilon_f' + A_a(\varepsilon_s - \varepsilon_f')]} \tag{4.50}$$

Equation 4.50 can be generalized for a random distribution of orientation and the final general form is

$$(\varepsilon - \varepsilon_f) = 1/3\,(1 - \phi)(\varepsilon_s - \varepsilon_f) \quad \frac{\varepsilon_f'}{abc \quad [\varepsilon_f' + A_a(\varepsilon_s - \varepsilon_f')]} \tag{4.51}$$

Different expressions could be obtained from this general expression Equation 4.55, depending on the values of A_i which represent particle shape. ε_f' lies in the range of $\varepsilon_f \leq \varepsilon_f' \leq \varepsilon$. As a special case, consider a spherical particle of depolarization factors $A_a = A_b = A_c = 1/3$, thus Equation 4.51 can be simplified to

$$(\varepsilon - \varepsilon_f) = \frac{3(1 - \phi)\ (\varepsilon_s - \varepsilon_f)\,\varepsilon_f'}{(2\varepsilon_f' + \varepsilon_s)} \tag{4.52}$$

For small concentrations $\varepsilon_f' = \varepsilon_f$ then Equation 4.52 becomes

$$(\varepsilon - \varepsilon_f) = \frac{3\varepsilon_f\,(1 - \phi)(\varepsilon_s - \varepsilon_f)}{(2\varepsilon_f + \varepsilon_s)}$$

which can be written as

$$\frac{\varepsilon - \varepsilon_f}{3\varepsilon_f} = (1 - \phi)\ \frac{\varepsilon_s - \varepsilon_f}{2\varepsilon_f + \varepsilon_s} \tag{4.53}$$

Based on the previous assumption if $(1-\phi)(\varepsilon_s - \varepsilon_f)/(2\varepsilon'_f + \varepsilon_s)] << 1$, then Equation 4.52 can be generalized as

$$(\,\varepsilon - \varepsilon_f) = \frac{\dfrac{3(1 - \phi)\,(\varepsilon_s - \varepsilon_s)\,\varepsilon_f'}{(2\varepsilon_f' + \varepsilon_s\,)}}{1 - \dfrac{(1 - \phi)\,(\varepsilon_s - \varepsilon_s)}{(2\varepsilon_f' + \varepsilon_s)}} \tag{4.54}$$

or by taking $\varepsilon_f' = \varepsilon_f$

$$\frac{(\varepsilon - \varepsilon_f)}{(\varepsilon + 2\varepsilon_f)} = (1 - \phi) \frac{\varepsilon_s - \varepsilon_f}{\varepsilon_s + 2\varepsilon_f} \qquad (4.55)$$

Equation 4.54 is the Rayleigh mixing law, which is sometimes designated as the Clausius-Mossotti Equation and is derived for systems consisting of spheres of dielectrric constant ε_s dispersed in a medium of dielectric constant ε_f. The volume fraction for the sphers is $(1-\phi)$ where ϕ is the fluid volume fraction.

This equation forms the basis from which the effective medium theory is derived. The dispersed spheres are assumed to be coated with a skin made of coated spheres. Assume that a few grains of any size are added to the medium of ε_f. The new mixture will have a dielectric constant different from the original. This new mixture is used to coat some new grains. At each step a small amount of grain is added, and the dielectric constant of the new system is determined. If ε_h is the dielectric constant of the mixture at a given step h and it was used to coat additional grains of volume δv_s, then using Equation 4.54, the dielectric constant of ε_{h+1} of the mixture is given by

$$\frac{\varepsilon_{h+1} - \varepsilon_h}{\varepsilon_{h+1} + 2\varepsilon_h} \equiv \frac{\delta v_s}{V_f + V_s} \quad \frac{\varepsilon_s - \varepsilon_h}{\varepsilon_s + 2\varepsilon_h} \qquad (4.56)$$

V_f and V_s are the total volumes of the fluid and the solid, respectively. For an infinitesimal volume increment dv, Equation 4.56 gives

$$\frac{d\varepsilon}{3\varepsilon} \equiv \frac{dv_s}{V_f + V_s} \quad \frac{\varepsilon_s - \varepsilon}{\varepsilon_s + 2\varepsilon} \qquad (4.57)$$

ε is the dielectrtic constant of the mixture that is used to coat additonal solid grains of total volume dv. The volume fraction of the solid matrix at any step is given by

$$\gamma = \frac{v_s}{V_f + V_s} \qquad (4.58)$$

Differentiating Equation 4.58 gives

$$d\gamma = \frac{dv_s}{V_f + V_s} \quad \frac{v_s dv_s}{(V_f + V_s)^2}$$

$$= (1 - \gamma) \frac{dv_s}{V_f + V_s} \tag{4.59}$$

Using Equation 4.59 in Equation 4.57 gives

$$\frac{d\varepsilon}{3\varepsilon} = \frac{d\gamma}{1-\gamma} \frac{\varepsilon_s - \varepsilon}{\varepsilon_s + 2\varepsilon} \tag{4.58}$$

Integrating the last equation for $\gamma = 0$, where the solid is not introduced, to $\gamma = 1-\phi$, the total volume fraction of the solid as shown in Equation 4.48, with the boundary conditions that $\varepsilon = \varepsilon_f$ at $\gamma = 0$ and $\varepsilon = \acute{\varepsilon}$ at $\gamma = 1 - \phi$, then

$$\frac{\varepsilon - \varepsilon_s}{\varepsilon_f - \varepsilon_s} {\frac{\varepsilon_f}{\varepsilon}}^{1/3} = \phi \tag{4.61}$$

Equation 4.65 is a special form of EMT where the solid matrix has spherical shape. The general formula has an exponent A instead of the 1/3. The exponent A is a constant depending on the choice of the depolarization factors A_i of Equation 4.51.

The major disadvantage of EMT is its limitation in application to two-component systems. The mixture formula for a three component system may be derived by repeatedly using Equation 4.61. For example, if the system is composed of a fluid, a solid and water, the EMT expression can be used to obtain the dielectric constant of the solid and the fluid, then used again to calculate the dielectric constant of water and solid-fluid mixture.

Looyenga and Landau-Lifshitz Equation

Another approach to driving Equation 4.54 was introduced by Looyenga (1965) and Landau and Lifshitz (1960). In this approach it was assumed that for the two-component system the dielectric constant of the constitutents change so that $\varepsilon_f \rightarrow \varepsilon - \Delta\varepsilon$ and $\varepsilon_s \rightarrow \varepsilon + \Delta\varepsilon$. Applications of these conditions to equation 4.54 (Hasted, 1973), leads to

$$\varepsilon = [\varepsilon_f^{1/3} f + \varepsilon_s^{1/3} (1 - \phi)]^{1/3} \tag{4.62}$$

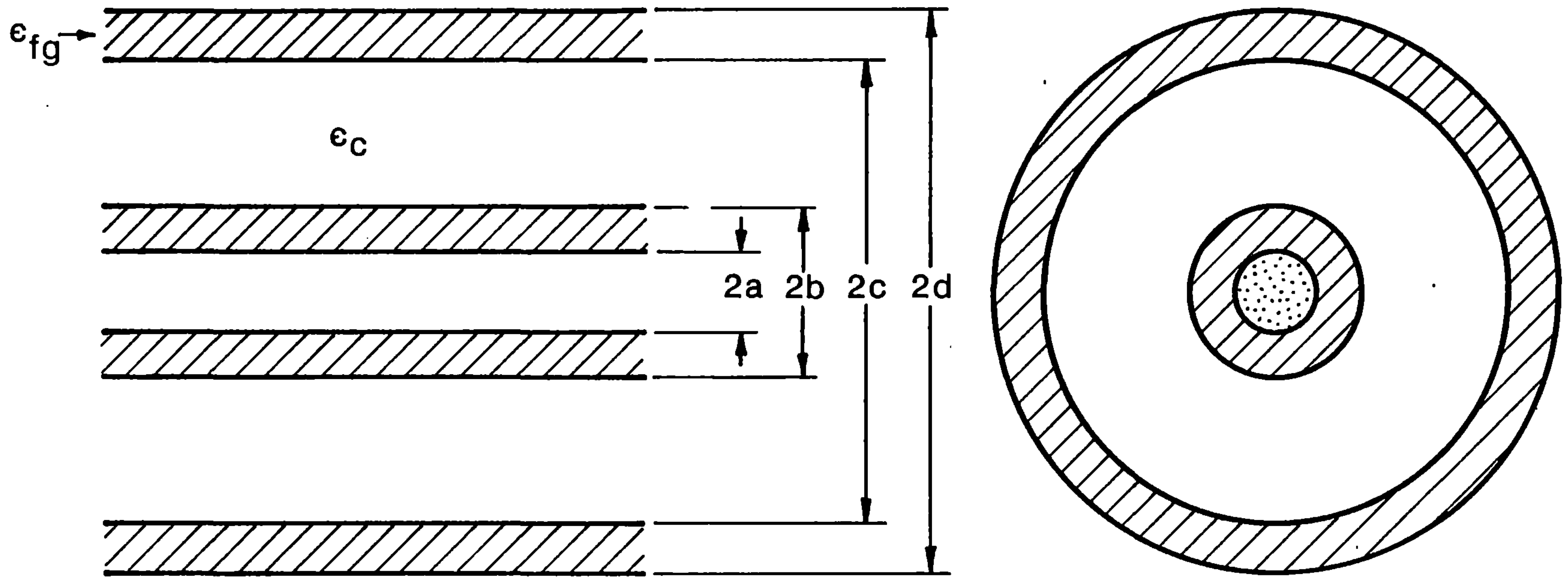
Equation 4.62 could also be deduced from the general formula of Equation 4.17 for c = 1/3

Correction Formula for Consolidated Materials

When the material under investigation is consolidated, a core sample can be machined into a circular cylinder with a concentric circular hole drilled to fit the coaxial line. Figure 10 shows the longitudal and cross sectional views of the samples contained in the coaxial line. The unavoidable gaps between the core samples and the conductors have a measurable effect on the measurements and calculations of the dielectric constant of the sample. As the electromagnetic wave is introduced to sample, part of it propagates through the solid core sample, and the rest propagates through the fluid gaps. Region (c-b) is occupied by the core sample while regions (b-a) and (d-c) are the fluid gaps.

The measured dielectric constant of the coaxial line does not represent the dielectric constant of the sample, rather it is the measured dielectric constant (ε_m) of the system inside the transmisson line. Thus the measured values should be corrected to extract the composite dielectric constant of the core sample. The MIT waveguide handbook (Marcutitz, 1954) derives a formula to calculate the dielectric constant of core maerials in terms of the wavelength and dielectric constant of the core and fluid filling the gaps. In the derivation the outer radii are assume equal (i.e. c = d). The relationship is given as

$$\frac{\lambda_g{}^2}{\lambda_o} = \frac{{}^1/\varepsilon_{fg} \ln({}^b/a) + {}^A/\varepsilon_c \ln({}^c/b)}{\ln({}^b/a) + A \ln({}^c/b)} \tag{4.63}$$



(a) LONGITUDINAL VIEW

(b) CROSS SECTIONAL VIEW

Figure 10. Longitudinal and cross sectional views of the transmission line with a sample core inside it. The core radii are b and c while a is the radius of the center conductor and d is the radius of outer conductor. The gaps between the coaxial line are occupied by a fluid of dielectric constant ε_{fg}. ε_c is the sample dielectric constant.

where ε_{fg} is the dielectric constant of the fluid filling the gap, ε_c is the dielectric constant of the core sample, called the corrected dilectric constant, λ_o is the free space wavelength, λ_g is the wavelength of the waveguide and A is approximately one. The wavelength can be related to the dielectric constant using the velocity of the propagation in the medium. Thus using Equation 3.1

$$\frac{\lambda_g}{\lambda_o} = \frac{C}{C_o} = \frac{C_0/\sqrt{\varepsilon_m}}{C_o} = \frac{1}{\sqrt{\varepsilon_m}} \tag{4.64}$$

where C_0 and C are the velocity of propagation in free space and in the waveguide, respectively, and ε_m is the measured dielectric constant of all materials contained in the waveguide. Substitution of Equation 4.64 into Equation 4.63 yields

$$\varepsilon_m = \frac{\ln({}^{c}/a)}{{}^{1}/\varepsilon_{fg} \ln({}^{b}/a) + {}^{1}/\varepsilon_c \ln({}^{c}/b)} \tag{4.65}$$

If the outer radii c and d are not equal, then a gap between the core and outer conductor is present which will affect the calculations. If such affect is included, Equation 4.65 will then be modified to

$$\varepsilon_m = \frac{\ln({}^{d}/a)}{{}^{1}/\varepsilon_{fg} \ln({}^{b}/a) + {}^{1}/\varepsilon_c \ln({}^{c}/b) + {}^{1}/\varepsilon_{fg} \ln({}^{d}/c)} \tag{4.66}$$

The required parameter is ε_c which could be written as

$$\varepsilon_c = \frac{\ln({}^{c}/b)}{{}^{1}/\varepsilon_m \ln({}^{d}/a) - {}^{1}/\varepsilon_{fg} \ln({}^{b}/a) - {}^{1}/\varepsilon_{fg} \ln({}^{d}/c)} \tag{4.67}$$

Equation 4.67 is called the correction formula which extracts the dielectric constant of the core sample (ε_c) from the known parameters (i.e., a, b, c, d and ε_{fg}) and the measured value, ε_m.

The procedure which was applied to the unconsolidated materials is used for consolidated materials to determine the porosity, ϕ, and the solid dielectric constant, ε_s, for the core sample. Mixing laws are then applied to the corrected dielectric measurements to compare them with the calculated results for fully and partially saturated samples.

Emulsion Theory

Emulsions are a dispersion of one immiscible liquid in another immiscible liquid in the form of droplets of microscopic size. In most emulsion systems, water is one of the immiscible fluids. The other liquid is usually organic in nature and is generally referred to as the oil phase, regardless of its structure. There are two types of emulsions; in one type, the oil is dispersed throughout the water in the form of droplets. This is called an oil-in-water emulsion and is abbreviated o/w. The oil is referred to as the dispersed or internal phase and water as the continuous or external phase. In the second type of emulsion, the situation is reversed and water is dispersed throughout the oil phase. This is called the water-in-oil emulsion and abbreviated w/o. In this system oil is the continuous phase and water the dispersed phase.

There has been a disagreement on the maximum value which can be allowed to form a certain type of emulsion. It was believed that the percentage has to follow the phase-volume theory (Acosta, 1979), while Gopal (1968) claimed that it has nothing to do with this theory because the liquid droplets are by no means spherical solids. The phase-volume theory shows that if small equidimensional spheres are closely packed together into a given space, they occupy approximately 74% of the total available volume, independent of the sphere's size. According to this theory it is not possible to have two different types of emulsions over a particular range of concentration. For example, 15% oil and 85%

water could form only an oil-in-water emulsion. If oil is continually added to the system, the distance between the oil globules decreases until they touch each other and coalesce (Figure 11). A w/o emulsion forms at this concentration of oil where oil becomes the continuous phase and water is the nonconnected phase. However, the issue depends on the emulsifier used in the emulsion because Hania, (1968) formed o/w and w/o emulsions for the two fluids at all percentages of concentration, using different emulsifiers for the different ranges of emulsions.

Surface-Active Agents (Emulsifiers)

A surface-active agent is a compound attracted to and adsorbed at the interface. The interface can be the surface of a liquid or the boundaries between two immiscible liquids, a solid and a liquid or two solids. The term surface-active agent is a general designation for all materials which are surface active and for emulsions are classified as emulsifiers.

In order to possess the property of surface activity, a material must have a specific type of molecular structure. As a general rule, surface-active agents have two different parts: a polar part and a non-polar part. The polar section is designed to have an affinity to water and is termed the hydrophilic (water-loving) portion. The other part of the molecule has an aversion for water and is called the hydrophobic (water-hating) or lipophilic (oil-loving) portion. Thus, surface-active agents are constructed with two, almost opposite, parts (hydrophilic and hydrophobic). Therefore, a molecule with this type of structure will seek a region, such as oil-water interface, where it can satisfy its solubility tendencies by replacing oil and its hydrophilic polar head in the aquous phase. Surface-active agents are divided into three groups: anionic, nonionic and cationic (Schwartz et al. 1958).

In the case of w/o emulsion the droplets of water are coated with emulsifier with their ionic heads (water soluble) in the water while the counter ions (oil soluble) are in the oil. Such droplets are electrically neutral. On the other hand, in o/w emulsion the oil

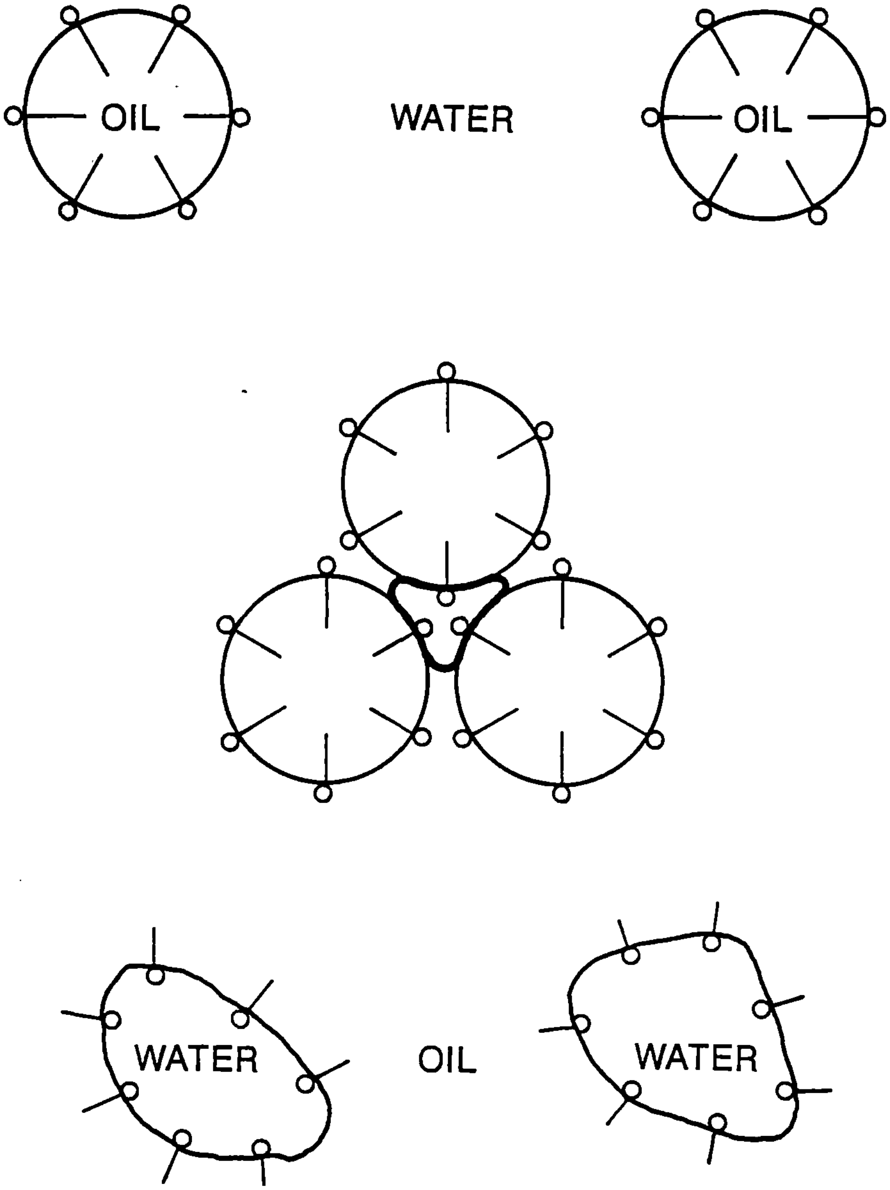


Figure 11. Mechanism of Phase Inversion. Addition of oil to an o/w emulsion unites the oil phase and traps water as the dispersed phase.

droplets are surrounded by negative ions resulting in a repulsion bertween the droplets (Figure 11).

The theory of emulsion focuses on the fact that the interfacial interaction is the main contributor to the emulsion. It has been shown (Acosta, 1983) that the characteristics of the interfacial film are of prime importance for the development of a stable emulsion. The amount of emulsifiers (surfactants) present in a system greatly affects the emulsion stability of a water-in-oil fluid having a high oil concentration and the stability of the emulsions is not dependent on the interfacial film, but on the ability of the film to absorb the emulsifier present in the system.

Another theory of emulsion formation is that the stability of an emulsion is due to the ionic charges of the internal phase. These charges occur as a result of ionization, droplet contact, or absorption. As mentioned earlier for o/w emulsion, the development of a surface charge from the ionization of the emulsifier can be easily understood. The electrical repulsion between the droplets will prevent the coalescence which will contribute to the stability of an emulsion.

Flow of Fluids Through Porous Media

Fluid flow in porous media requires a knowledge of properties and configuration of both media and the fluid. A porous media is generally an extremely complex network of channels. The actual geometry and flow patterns of typical systems is too complex to be described in microscopic detail as the fluid velocity varies drastically from point to point. For this reason, flow through porous media is generally described in terms of macroscopic velocities over the total volume of the medium. The detailed flow pattern is thus ignored and the conducting body is treated as though it were a uniform medium, with the flow spread over the entire cross section, solid and pore space alike.

In multiphase fluid systems in porous media, forces acting at the interface between the two fluids are important in describing flow properties. The combination of all active surface forces determines the wettability and capillary pressure of a porous medium, which in turn, affect the flow and the storage of fluid in the medium.

The tendency of a liquid to spread over the surface of a solid is an indication of the wetting characteristics of the liquid for the solid and is called the wettability. The adhesion tension, which is a function of the interfacial tension, determines which fluid will preferentially wet the solid. Consider two immiscible fluids (water and oil) contained in a porous medium with a hypothetical interface as in Figure 12. At equilibrium, the two hydrostatic equation define the state of the interface are

$$P_o - P_w = \sigma_{ow} R_{ow} \tag{4.68}$$

$$A_T = \sigma_{os} - \sigma_{ws} = \sigma_{ow} \cos \theta_{ows} \tag{4.69}$$

where A_T is the adhesion tension, P_o is the pressure in the oil, P_w is the pressure in the water; σ_{ow} is the interfacial tension between the two fluids, R_{ow} represent the curvature of the interface, and θ_{ow} is the constant angle measured through the denser liquid phase and range from 0 to 180°. The contact angle θ_{ow} is used to define the wettability of the solid surface and for this example (Greenkorn, 1983) the solid is water wet if $\theta_{ow} < 40°$. If $40 < \theta_{ow} < 140°$ then the solid surface is said to have neutral wettability.

The capillary pressure, P_c, of a system is defined as the pressure gradient in the two liquids when a capillary tube with radius r is placed in a large open vessel containing a liquid. The capillary pressure is usually expressed as

$$P_c = \frac{2\,\sigma \cos \theta}{r} \tag{4.70}$$

where σ is the interfacial tension between the two fluids. From this equation, it is observed that P_c is a function of the adhesion tension ($\sigma\cos\theta$) which determines the wetting characteristics and leads to the statement that the greater the affinity of the denser phase for the solid, the greater will be the capillary pressure across the interface. Consider a porous medium saturated with a wetting fluid and assume the contact angle is zero. For displacement of the wetting fluid by a nonwetting fluid the capillary pressure increases as the saturation of the wetting fluid decreases. A plot of capillary pressure (P_c) versus wetting fluid saturation (S_w) is shown in Figure 13. The curve is called drainage or drying curve. The reverse process, where the wetting is displacing the nonwetting fluid is called imbibition or wetting curve. For imbibition, P_c decreases as the wetting saturation increses. The general shape of the curves bears out the fact that no displacement occurs until a certain minimum displacing pressure is reached in the displacing phase, and that always a certain residual saturation of the displaced fluid remains no matter how great a pressure is applied in the displacing fluid.

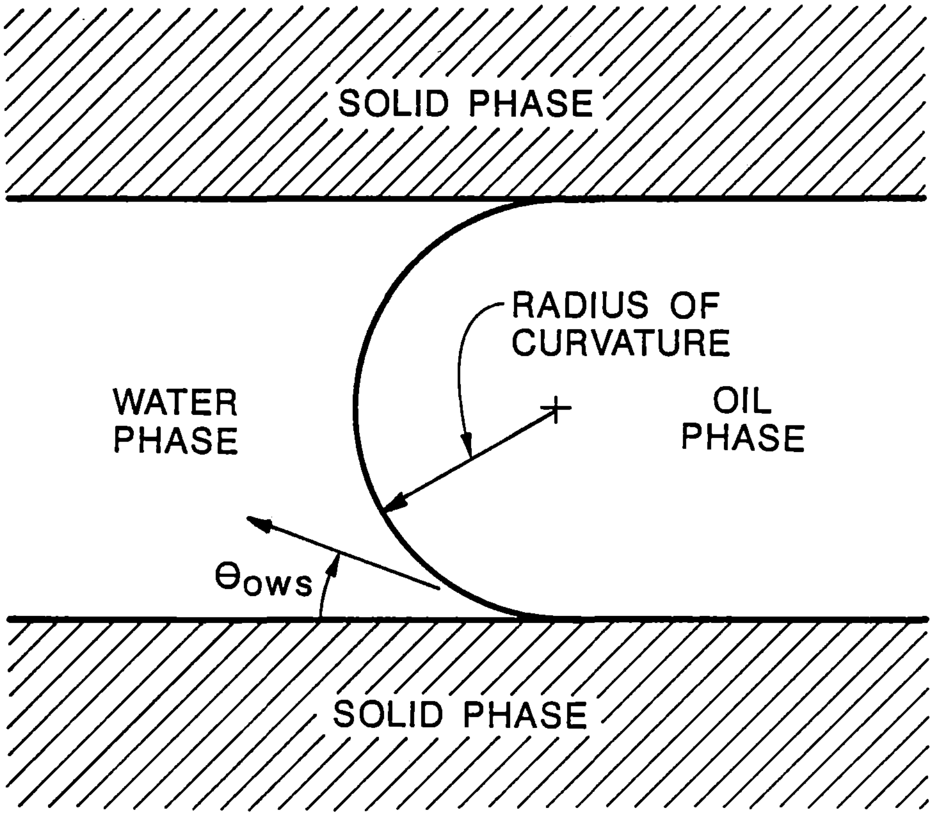


Figure 12. Hydrostatic Equilibrium: Two Fluid Phases on Contact With a Solid Phase

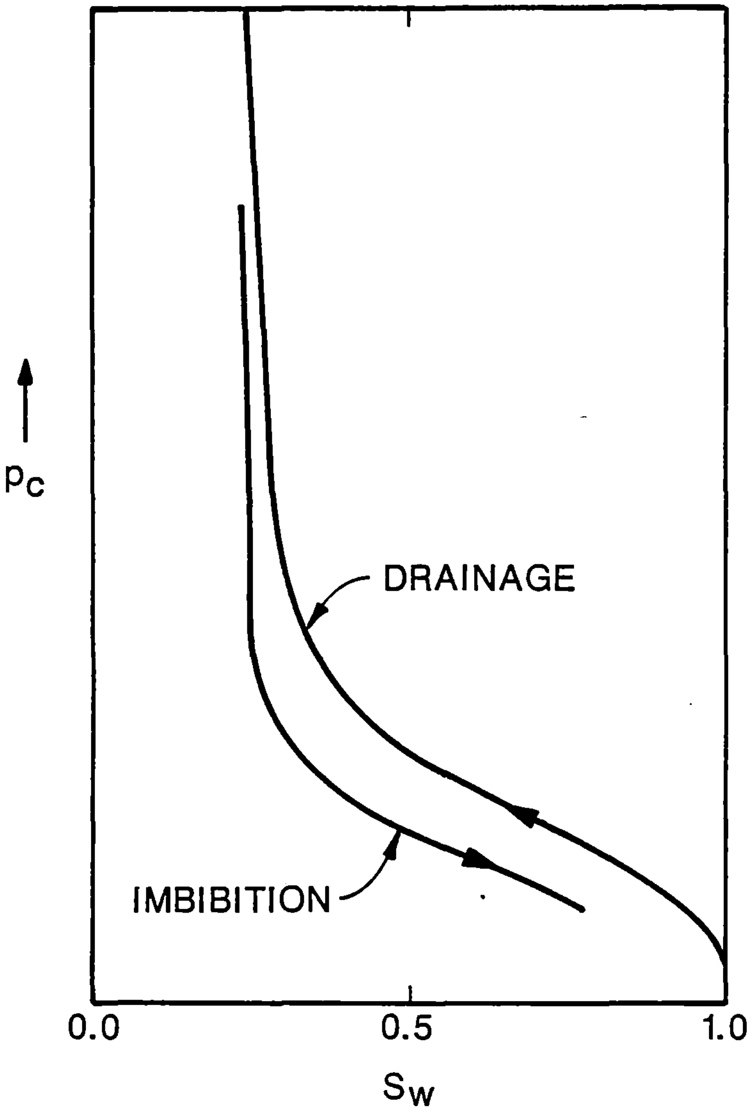


Figure 13. Capillary Pressure as a Function of Water Saturation.

CHAPTER V

RESULTS AND DISCUSSION

Introduction

This chapter considers the application of the dielectric mixing laws to various composite materials. The experimental results provide a basis to evaluate the applicability of the mixing laws to a wide range of composite materials. Those materials include both consolidated and unconsolidated porous solids as well as emulsions and solutions. Procedures are developed which allow application of the mixing laws to multicomponent systems. Simple empirical expressions are also developed which relate dielectric measurements to water content using a minimum prior knowledge of the detailed composition of the porous systems. These relations are applied to soils and are shown to have wide applicability over various soil types in a particularly simple form. The range of application and measurement procedures necessary to use various forms of the mixing equations is determined for a wide range of composite systems.

The dielectric mixing laws are also applied to a unique dynamic system in which multiple fluids flow through the porous material. The flow rates and retention of various fluid components are determined using this new monitoring technique. This flow monitoring technique offers several advantages including application when miscible flow components are involved. Application of this technique to systems which are characteristic of pollution transport and enhanced oil recovery procedure demonstrate its versatility.

Determination of the solid porous structure dielectric constant

Calculation of composite dielectric constant requires the knowledge of the dielectric constant of the constituent components and their volume fractions. For most materials, the dielectric constant of solid matrices are unknown and must be determined experimentally. The procedure adopted is to make measurements on dry samples (air saturated) and apply the proper mixing laws. Air measurements are taken as a reference since air has a known dielectric constant independent of frequency. The solid dielectric constants ε_s, obtained using this procedure varies depending on the laws to evaluate the dry sample measurement. If the measured dielectric constant of the dry sample as ε_0, then using the general empirical formula (Eq. 4.17), the composite dielectric constant is

$$\varepsilon^c{}_0 = [\varepsilon^c{}_a\phi + (1 - \phi)\varepsilon^c{}_s] \qquad (5.1)$$

where ε_a and ε_s are the dielectric constant of air and solid matrix while ϕ and $(1-\phi)$ are their respective porosities. If the parameters other than the matrix dielectric constant ε_s in Equation (5.1) are known, then

$$\varepsilon_s = \frac{[\varepsilon^c{}_0 - \varepsilon^c{}_a\phi]^{1/c}}{(1-\phi)^{1/c}} \qquad (5.2)$$

It is clear from Equation 5.2 that the value of ε_s depends on the empirical exponent c. When the Effective Medium Theory (EMT) is applied, higher values of matrix dielectric constant are obtained than those determined from other mixing laws of Equation 5.2. The dry dielectric constant resulting from applying various mixing laws are listed in Table IV.

Using values of ε_s determined from this procedure, and ε_f (dielectric constant of the saturating fluid), the mixing laws can be applied to saturated media to determine the composite dielectric constant. The procedure adopted to compare the mixing laws with the measured results is first to determine the solid matrix dielectric constant evaluating the air

TABLE IV

THE DEPENDENCE OF THE SOLID DIELECTRIC CONSTANT (ε_s) ON THE MIXING LAWS. ALL VALUES ARE DERIVED FROM THE MEASURED DRY SAMPLE AND THE CORRESPONDING MIXING LAW.

Material	SRE	TQE	EMT
Glass beads	4.95	5.29	6.15
Ottawa sand	3.63	3.48	3.89
Limestone	5.86	5.47	7.24
Sandstone	4.17	3.92	4.62

saturated measurements and then using the mixing law a second time to evaluate the composite dielectric constant of a liquid saturated porous structure.

This procedure was used to calculate the composite dielectrtic constant for various porous media. The solid dielectric constant (ε_s) was determined. The porous media were then saturated with different fluids which included liquids having various dielectric constants saturating various matrix configurations such as glass beads, sands and soils. Fluids with dielectric constants ranging from 2 to 80 were used to saturate the porous media.

The composite/fluid dielectric constant for glass beads 1 mm in diameter saturated with six reference fluids is shown in Figure 14. The measured values are compared with standard mixing laws curves which include the Time Propagation Method (TPO), Three Quarter Equation (TQE) and the Effective Medium Theory (EMT). The TPO is referred to as the Square Root Equation (SRE).

Since the dry sample measurement was considered as a reference point, all mixing laws intercept at $\varepsilon_f = 1$. For fluids of low dielectric constants ($\varepsilon_f < 10$) SRE and TQE mixing laws failed to agree with measurements. The failure is, in part, due to the low values of ε_s which had been used. The variation in ε_s due to the application of different mixing laws are listed in Table IV for various porous media. The low values for SRE and TQE lead to unrealistic results. For example, in the case of the glass beads ($\varepsilon_s = 4.95$, for TQE) saturated with chlorobenzene ($\varepsilon_f = 5.62$), the measured value was 6.08 while the calculated composite dielectric constant was 5.19. These are unexpected values because the measured value was higher than ε_s and ε_f which is unrealistic. However, for high ε_f the measurements are closer to TQE than other mixing laws. Figure 15 shows the composite/fluid dielectric constant relationship for ottawa sand. Although the physical properties of Ottawa sand are different from those of glass (uniform particles, but not spherical in shape) both materials show the same general trend. Geological materials which have irregular particle shapes, such as sandstone and limestone, were included in the

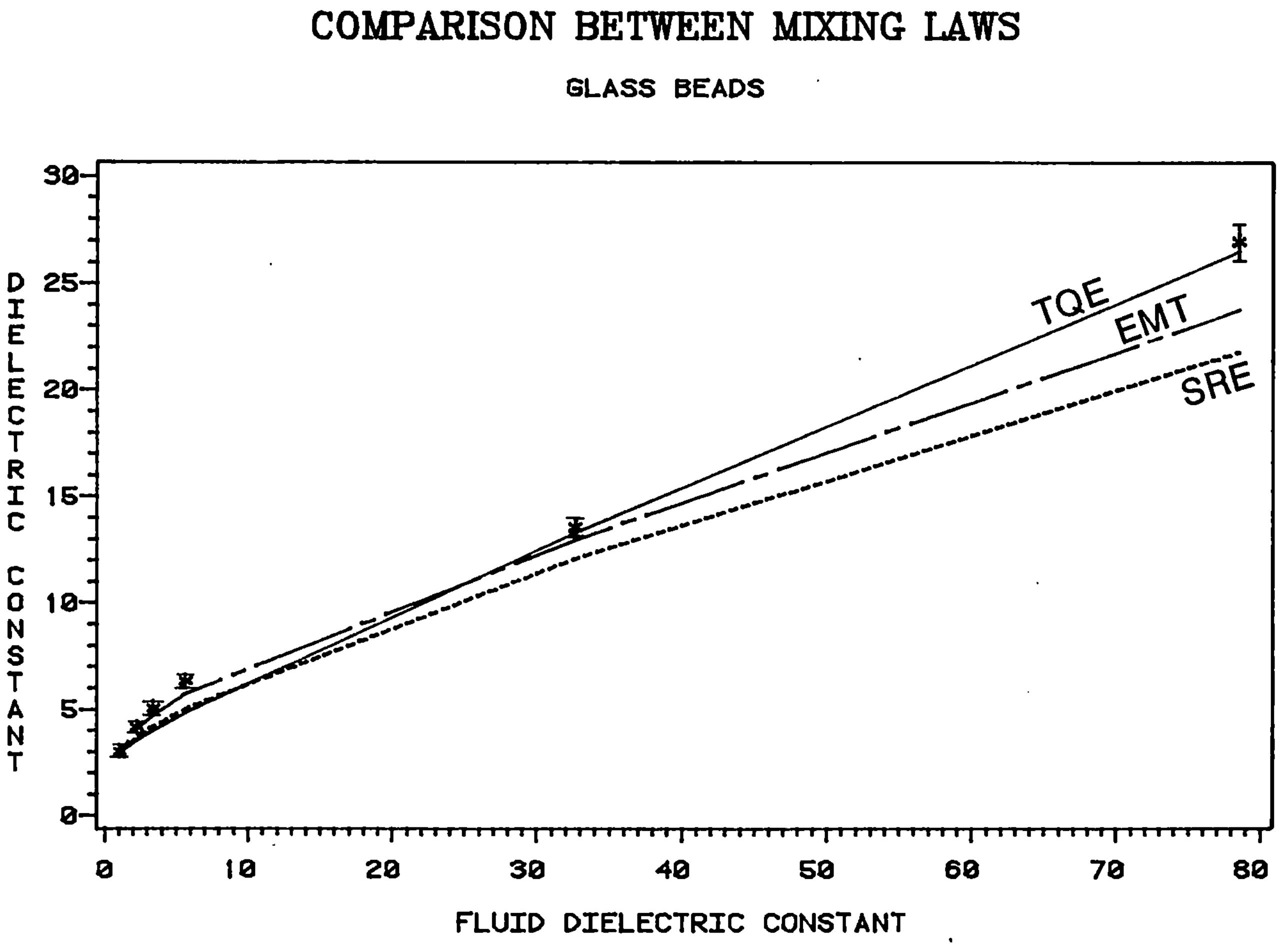


Figure 14. TQE shows a good agreement at high ε_f values. ε_s were determined for each mixing law.

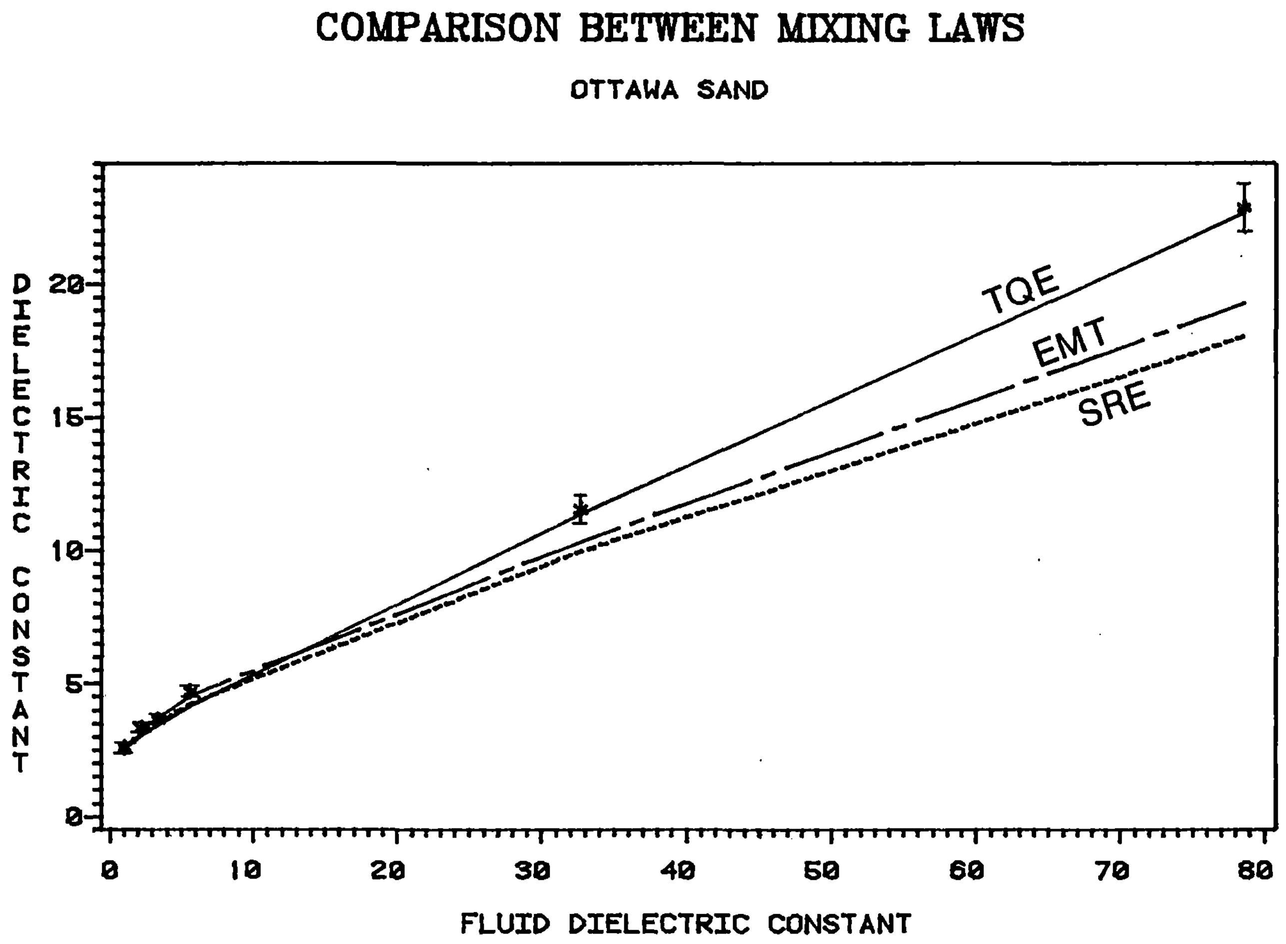


Figure 15. TQE shows a good agreement at high ε_f values. ε_s were determined for each mixing law.

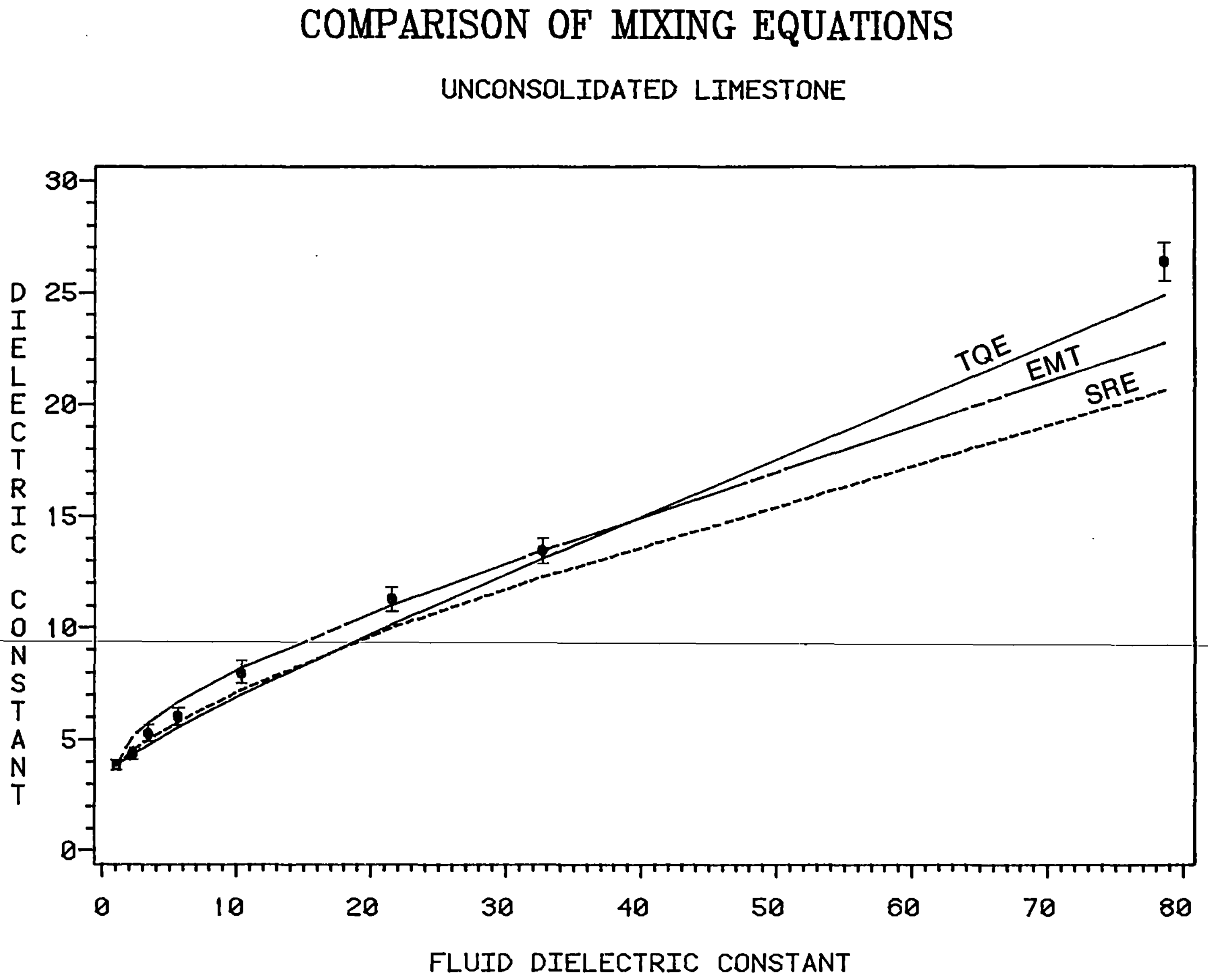


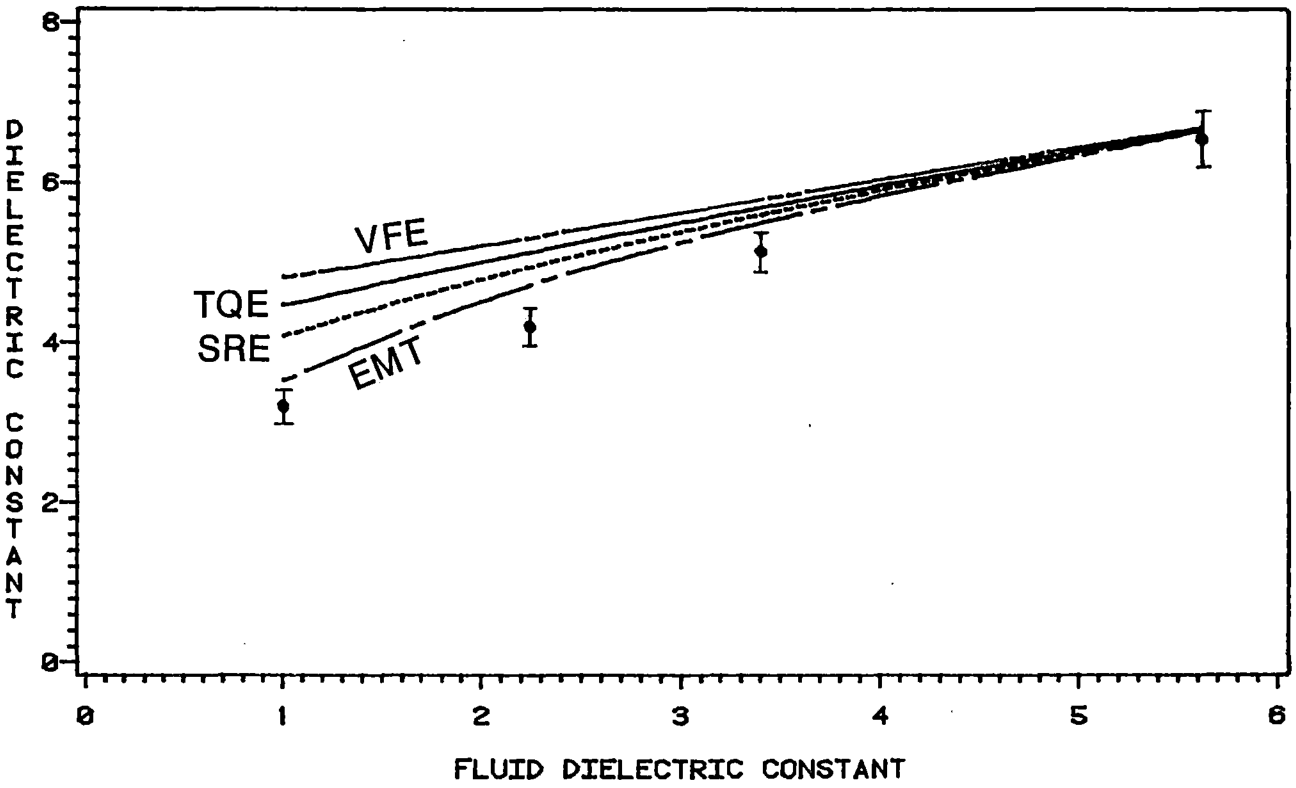
Figure 16. Similar to Figure 14 for limestone. The EMT has high values at low ε_f because its ε_s is higher than both SRE and EMT.

measurements. Sandstone shows similar behavior as those shown in Figure 15. Limestone, like glass beads, depicts some change in the behavior of the curves as shown in Figure 16. At low fluid dielectric constants, EMT curves seem to be different from other mixing laws, even though they agree at $\varepsilon_f = 1$. However, at high dielectric constant fluids TQE agreed better with the measured values.

Since the objective was to find the adequate mixing laws to use in dielectric measurement, it was thought using different ε_s for the same matrix does not resolve the problem properly. More appropriately, start with solids of known dielectric constants, then compare the measurements with the calculations from different mixing laws. This goal was achieved by using glass matrix which was supplied by the National Bureau of Standards (NBS) as explained in Chapter III. This glass is used in verifying and standardizing test methods used to determine dielectric constants of materials.

The preliminary measurements are to determine which of the mixing laws is more appropriate in determining ε_s from dry samples. For this reason only low dielectric constant fluids were used. Figure 17 shows the dielectric constant of NBS glass, as a function of ε_f, the fluid dielectric constant. Since a standard value of ε_s was used for all mixing laws they would not intercept at $\varepsilon_f = 1$, rather, the merging occurs at $\varepsilon_s = \varepsilon_f$ because all formulas lead to the same composite dielectric constant. The closest curve to the measured values is the EMT. This indicates that to have ε_s for a material the EMT would be a more accurate calculation.

This section concludes that to compare between different mixing laws one can not use different values of ε_s for one matrix in different mixing laws. This leads to two unrealistic results. First, the comparison between the formulas is not accurate as long as ε_s is not fixed for all mixing laws. Second, because the calcualtion of ε_s using TQE gives relatively lower values then EMT, which lead to unrealistic results where the measured values turned out to be larger than both fluid and solid dielectric constants which violates



COMPARISON BETWEEN MIXING LAWS

LOW DIELECTRIC CONSTANT FLUIDS SATURATING NBS GLASS

Figure 17. The EMT expression shows the closest agreement (ε_s = 7.45 and Φ = 0.40).

the assumption made for all mixing laws. This assumption states that the composite dielectric constant, ε, of two-component systems (ε_s and ε_f) should be between them. For example if $\varepsilon_s > \varepsilon_f$ then $\varepsilon_f < \varepsilon < \varepsilon_s$.

Unconsolidated Materials

Determination of the composite dielectric constant for unconsolidated materials requires the knowledge of

1. The solid dielectric constant, ε_s,
2. The dielectric constant of saturating fluid, ε_f
3. The volume fraction of each component, ϕ and $(1-\phi)$.

When a certain fluid is filling the entire pore volume, the material is said to be fully saturated, otherwise it is partially saturated. This section considers the unconsolidated materials when they are fully and partially saturated.

Fully Saturated Samples

The dielectric mixing laws cited in the literature are formulated based on a porous medium fully saturated with water. There has been a disagreement among scientists on the selection of a universal mixing law from the existing ones. TPO and CRIM were judged to be the proper mixing laws by Rau and Wharton (1982) and Shen et al., (1985). However, Sen et al., (1981) claimed earlier that they are not adequate and that EMT is the proper mixing law.

In the following, a study of the behavior of composite dielectric constants for different fully saturated materials and the applicability of different mixing laws is presented. The study includes the effect of the particle shape and the saturating fluid on the composite dielectric constant. The materials used included NBS glass matrix, glass beads, crushed glass beads, ottawa sand, limestone and sandstone saturated with fluids having wide range of dielectric constants.

NBS glass matrix saturated with various reference fluids (listed in Table I) was used to establish a datum for the measured values. The relationship between the composite/saturating fluid dielectirc constant for NBS glass is shown in Figure 18. Intermediate points plotted in the figure between methanol ($\varepsilon_f = 32.63$) and water ($\varepsilon_f = 78.54$) were obtained using relative mixtures of both reference fluids. As can be seen from the Figure, the mixing laws yielded the same composite dielectric constant when the saturating fluid and the matrix have equal dielectric constant values. This suggested that the high dielectric constant fluids ($\varepsilon_f > 10$) should be treated separately from those of low ε_f ($\varepsilon_f < 10$). For high dielectric constant fluids the measured values were closer to the TQE curve. The measured data points were drawn (Figure 19) with respect to the maximum and minimum values yielded by TQE and EMT. The boundaries of the curves were obtained by considering the tolerances in ε_s and ϕ for the particular matrix sample. The TPO was excluded from the analysis due to its disagreement with the measured values. The data shown in Figure 19 demonstrates that the TQE describes the data points more adequately for high ε_f than any of the other mixing laws. Furthermore, the data points suggest that the lower limit for the TQE is a better fit for the measured range. In the previous section the EMT was shown to fit the measurements at low ε_f, and was used to determine ε_s from the air saturated measurements.

The values of ε_s for nonstandard materials derived in the previous section were used in the mixing laws to determine their respective composite dielectric constants. Figure 20 shows the composite/fluid dielectric constant of glass beads saturated with the reference fluids. The Figure shows that the mixing laws do not intersect at $\varepsilon_f = 1$, unlike the previous section, and the interception occurs at $\varepsilon_f = \varepsilon_s$. For high ε_f, the measurements showed a good agreement with the TQE curve. On the other hand, all mixing laws illustrate similar behavior when the saturating fluids have low dielectric constant. Identical results were obtained for crushed glass beads with irregular particles, (Figure 21), indicating that the composite dielectric constant is relatively independent of the particle

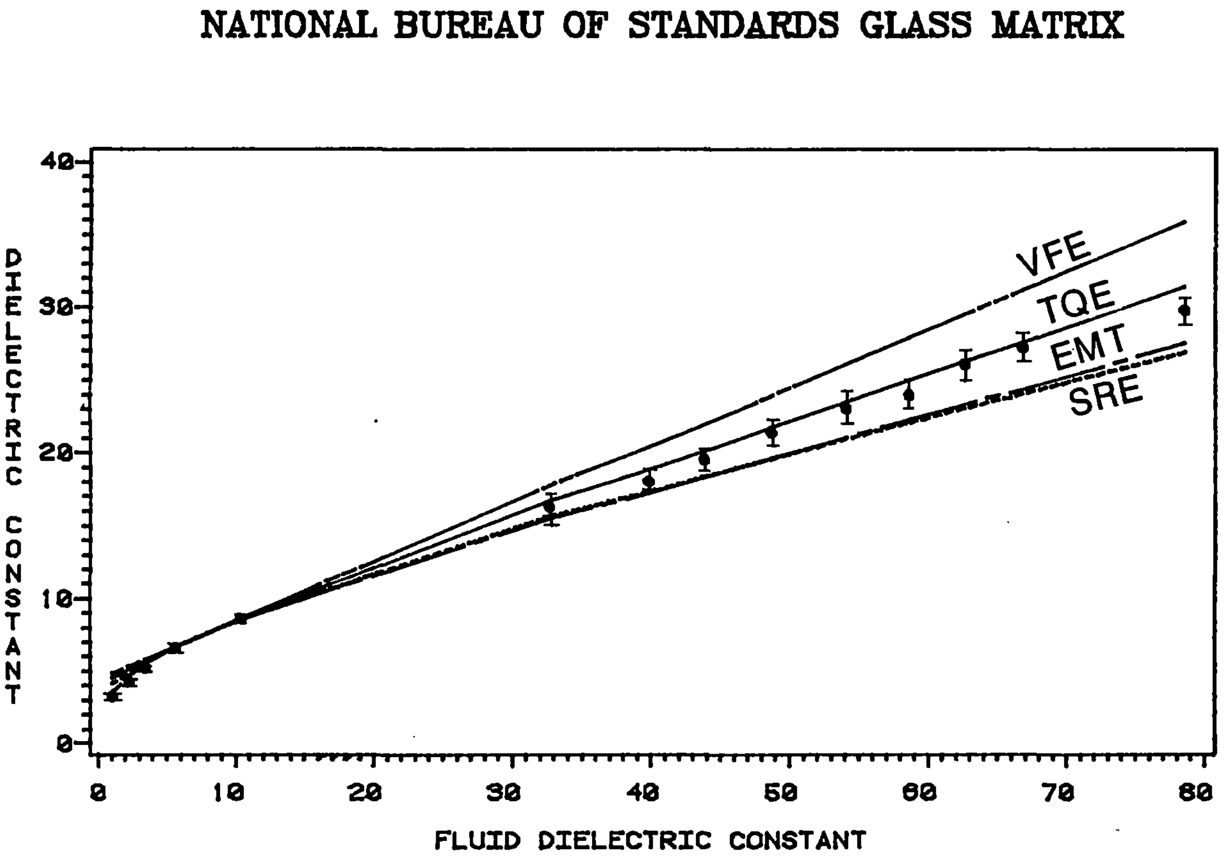

NATIONAL BUREAU OF STANDARDS GLASS MATRIX

Figure 18. A wide range of ε_f fluids saturating the NBS glass matrix. At high ε_f TQE is the closest to the measured values.

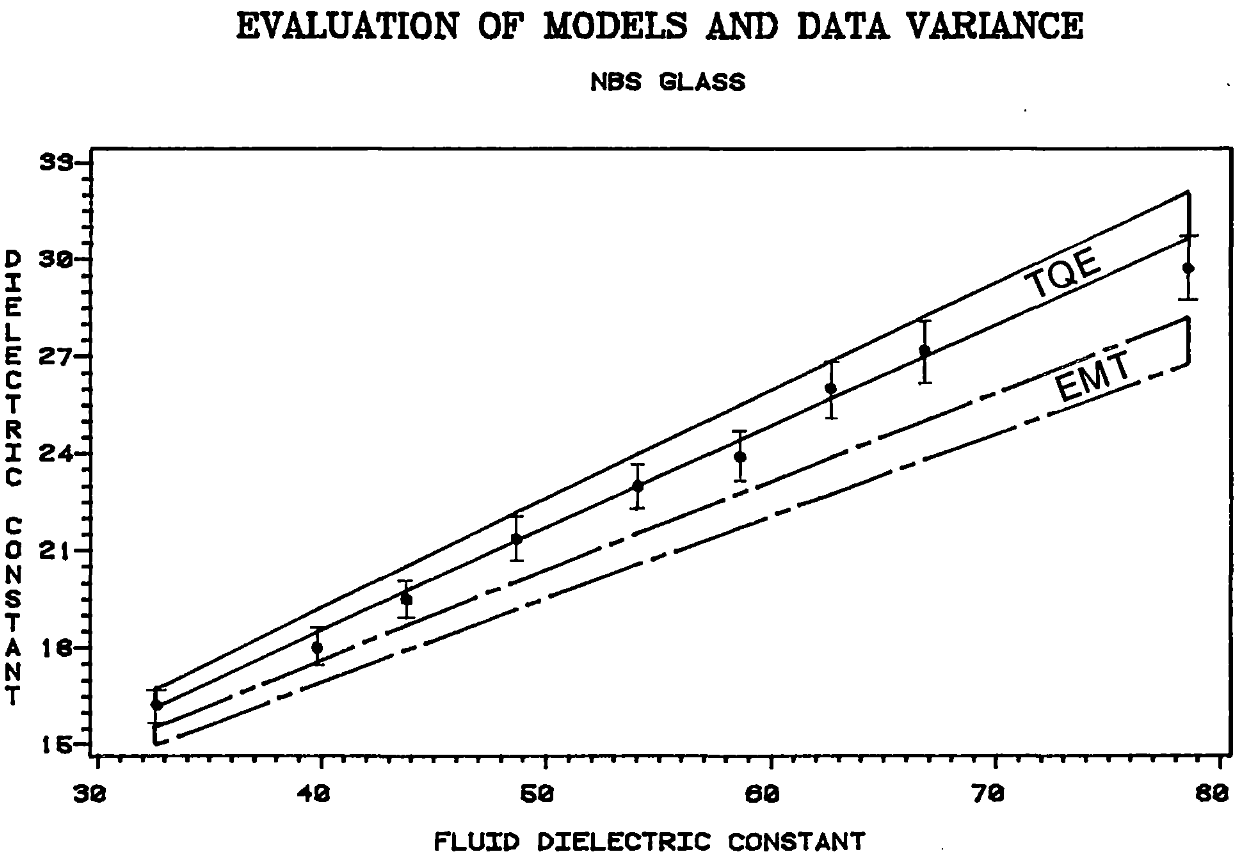


Figure 19. The curves show the tolerances in ε_s and Φ for NBS glass matrix in calculating TQE and EMT.

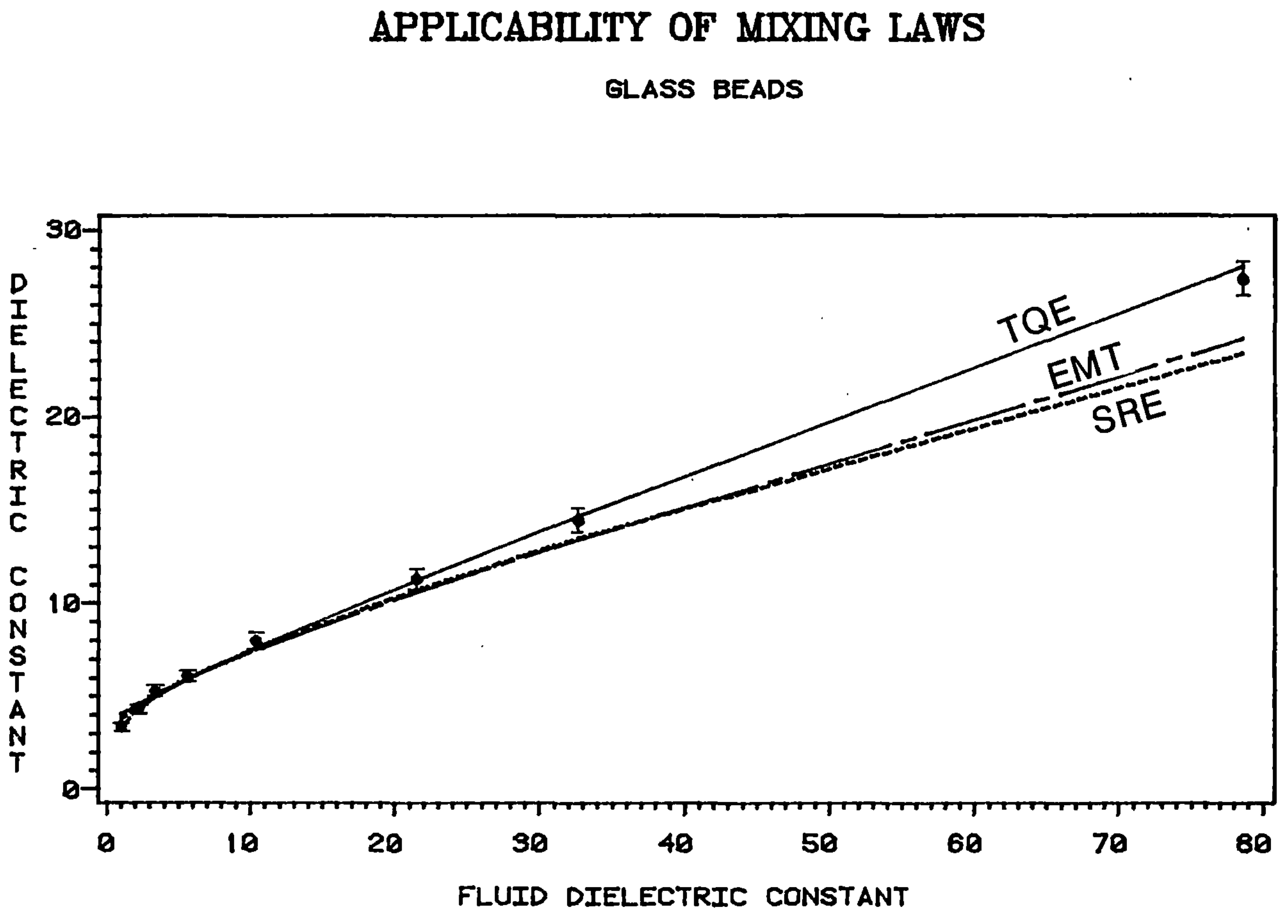


Figure 20. The comparison between the mixing laws when a common value for ε_s is used for all mixing laws.

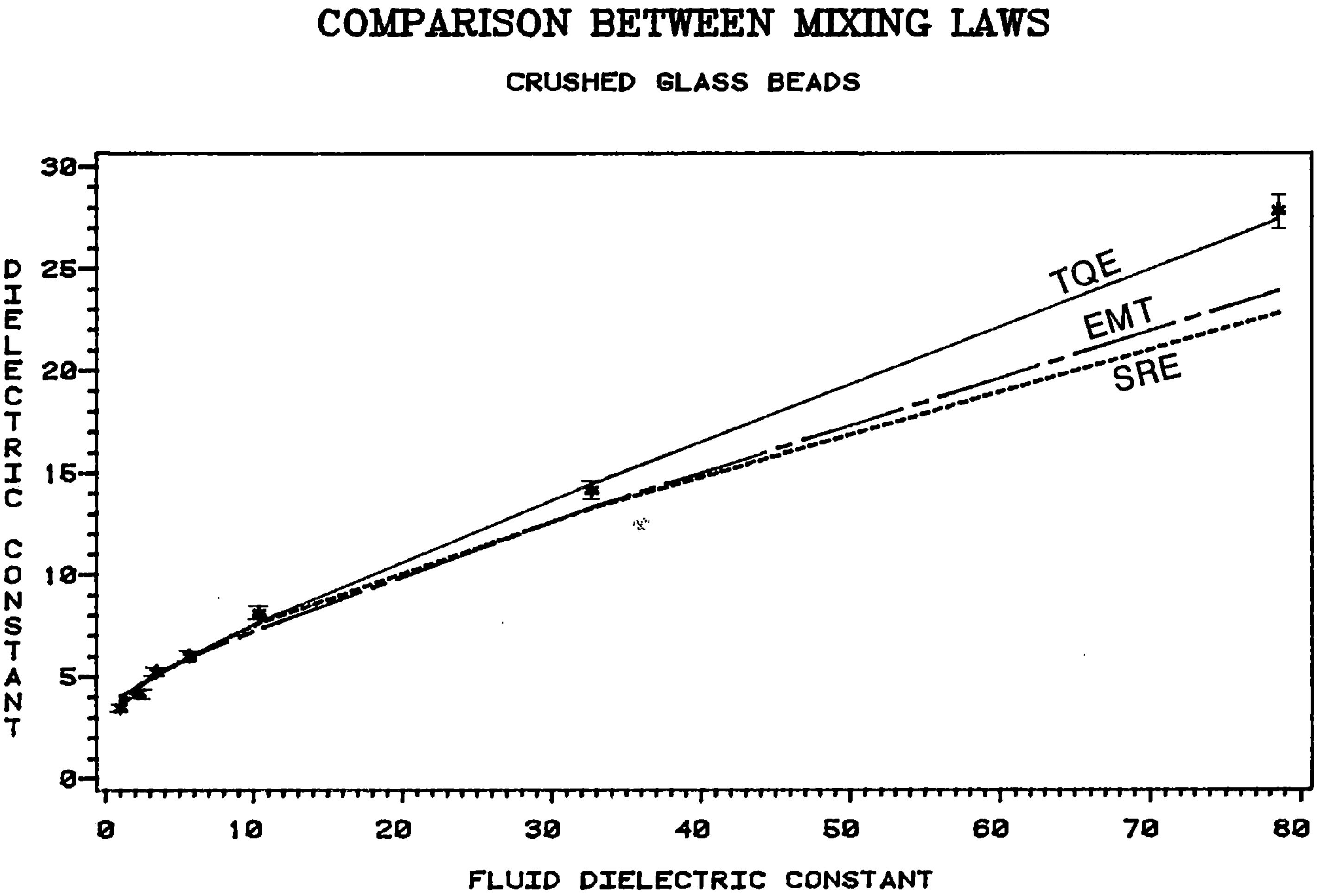


Figure 21. The comparison between the mixing laws when a common value for ε_s is used for all mixing laws.

shape. When the particle shape of the porous medium was uniform (but not spherical) the measurements agreed best with TQE at high ε_f, as can be shown in Figure 22 for ottawa sand. Identical results were obtained for irregular shapes of particles such as crushed limestone and sandstone, as shown in Figure 23 and 24.

The confusion in the literature over selecting the proper universal mixing law results because the porous media were fully saturated with only water. In contrast to these attempts, the work presented here was based on porous media saturated with various fluids in addition to water and the results obtained here have shown that a single law can never be applied as a universal law to determine ε for any matrix/fluid combination. The experimental results show that two mixing laws are applied over the range of pore fluids in fully saturated materials. When the fluid dielectric constant is less than the matrix the EMT is used, while when the pore fluid has a larger dielectric constant than the matrix the TQE is appropriate.

Partially Saturated Samples

A fully saturated material is considered to be a two component system consisting of only the solid marix and the saturating fluid. This system is rather ideal and rare in nature and the three or four-component system is, in fact, more realistic and frequently encountered. A three-component system consisting of a solid matrix with water and air filling the pores, is described as being partially (water) saturated. The following work will deal with such systems for different combinations of solids and fluids having air as a common component. The parameters of interest in this study were the water saturation, S_w, and the water content, θ_w. The first parameter is defined as the percentage of the water volume to the pore volume, while the second is the percentage of water volume to the total volume of the porous medium, regardless of its porosity.

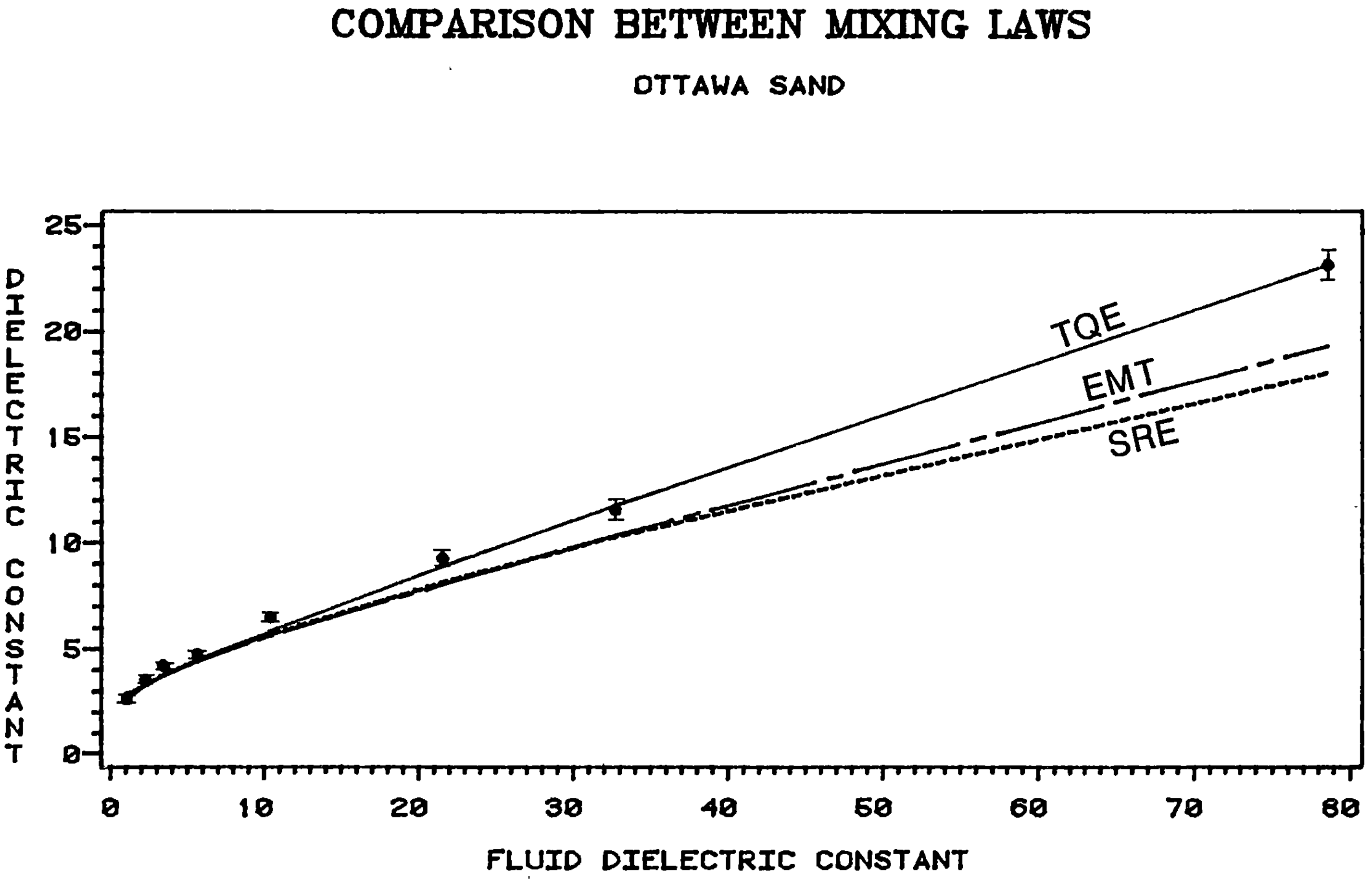


Figure 22. The comparison between the mixing laws when a common value for ε_s is used for all mixing laws.

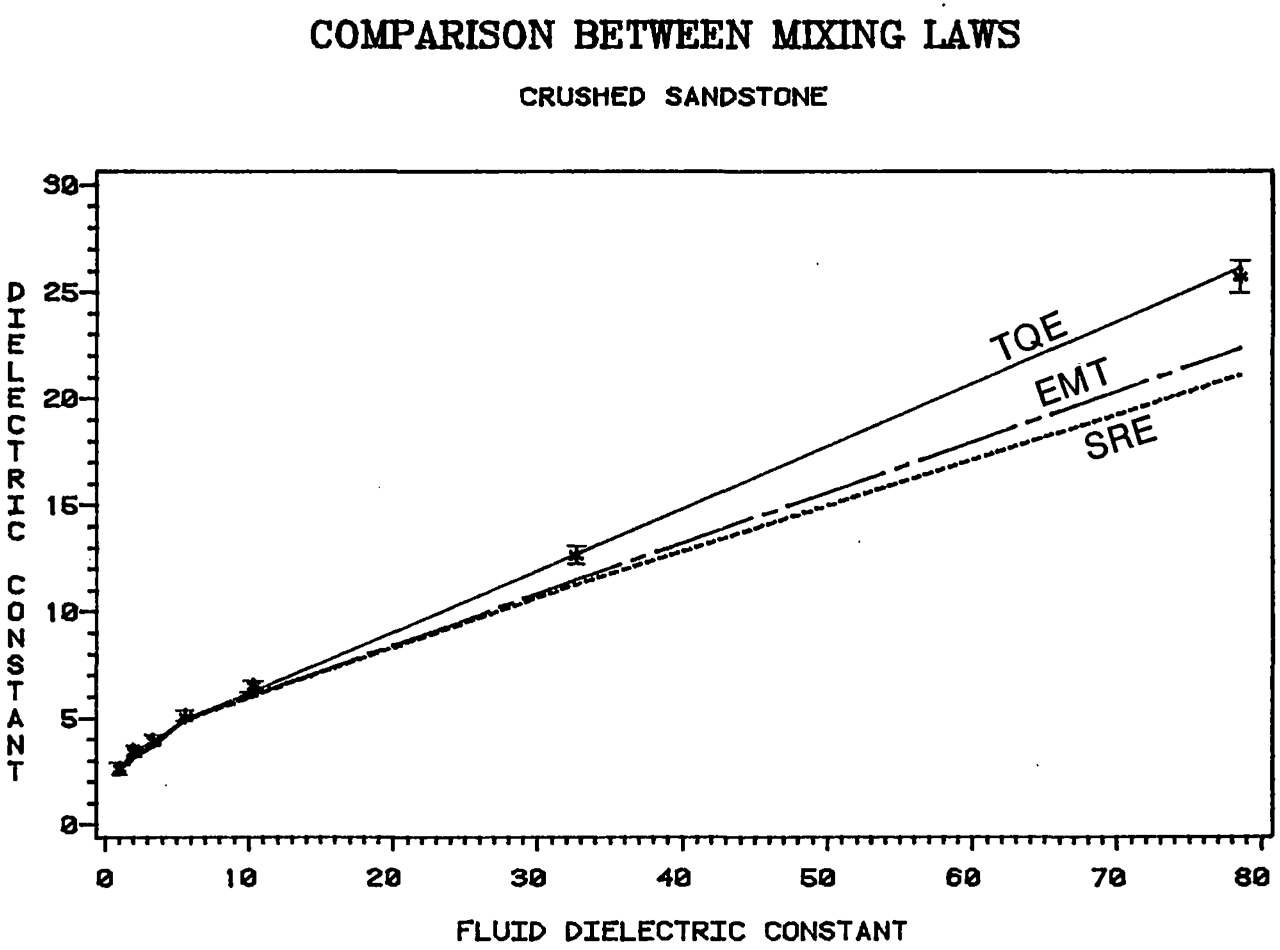


Figure 23. Crushed Sandstone as a Function of ε_f.

2. Testing the validity of the popular mixing laws, varying the porous media, the saturating fluids, and the consolidation of the system.

3. Determining applicability of the mixing laws, and other empirical formulae used to evaluate the water content and water saturation of soils and other porous media.

4. Employing the dielectric techniques to monitor the flow of fluids through porous media, to determine the storage capacity and the velocity of two fluid interface motion between two immiscible components.

CHAPTER II

REVIEW OF LITERATURE

Dielectric measurements applied to geological problems have recently attracted much attention. The reason for this stems, in part, from the large difference between the dielectric constant of water and any other component of a geological medium. The successful application of dielectric measurements depends on the solution of two problems. First, empirical relationships must be found which can accurately relate the composite dielectric constant properties to those of the constituents in the medium. Second, accurate values of the formation dielectric constant properties must be obtained independent of the water saturation measurements.

The present literature review includes a historical background of the theoeretical development of the empirical relationships referred to as "mixing laws." The development of the dielectric measuring techniques are also presented. The last section includes a discussion of the frequency ranges at which measurements are conducted and a comparison of previous measurements with certain dielectric mixing laws.

Historical Background of the Development of Mixing Laws

The study of heterogeneous media in the 19th century was closely related to the development of the molecular field concept, often connected with names like Clausius, Mossotti, Lorenz and Lorentz. It was Faraday, in 1837, who proposed a model of a dielectric which consisted of a series of metallic globules separated from each other by an insulating material. Clausius, in 1879, assumed that the molecules were conducting spheres. He then took each molecule as contained in a small sphere, cut out of the continuous surrounding medium, which is characterized by the final dielectric constant of the material. His analysis led to the following equation:

$$\alpha = \frac{3 \quad (\varepsilon - 1)}{4\pi N \quad (\varepsilon + 2)} \tag{2.1}$$

where ε is the dielectric constant of the medium, α is the molecular polarizability and N is the average number of molecules per unit volume. A subsequent step was made by Lorentz, in 1880, which was based on his own approach to electromagnetic (EM) theory. He assigned a refractive index, n, to the interior of the molecules which differs from the surroundings and derived a formula similar to Equation 2.1 with $\varepsilon = n^2$. This expression was independently derived by Mossotti in 1849 and Lorentz in 1870 and is, therefore, refered to as Clausius-Mossotti-Lorenz-Lorentz Relation.

Another earlier attempt to calculate the dielectric constant by mathematical analysis was made by Rayleigh in 1892. The system was assumed to be composed from spherical particles with a uniform radius arranged regularly at the lattice points of a simple cubic lattice in a continuous medium, i.e. a fluid. Rayleigh derived an equation for the effective dielectric constant of the system, ε, as follows

$$\varepsilon = \varepsilon_f \quad 1 + \frac{3\phi_s}{\dfrac{\varepsilon_s + 3\varepsilon_f}{\varepsilon_s - \varepsilon_f} - \phi_s - 1.65 \dfrac{\varepsilon_s - \varepsilon_f}{\varepsilon_b + 4/3\varepsilon_f} \phi_s^{10/3}} \tag{2.2}$$

Where ε_f and ε_s are the dielectric constant of the fluid and the solid, respectively, and ϕ_s is the solid volume fraction. This equation was later corrected by Runge in 1925 who substituted the coefficient 0.525 for 1.65, which appears in Equation 2.2, because of the omission of a factor of 1/π by Rayliegh. In 1904, J. C. Maxwell Garnett was working on glass containing small metal spheres, and he derived Equation 2.1 from Equation 2.2.

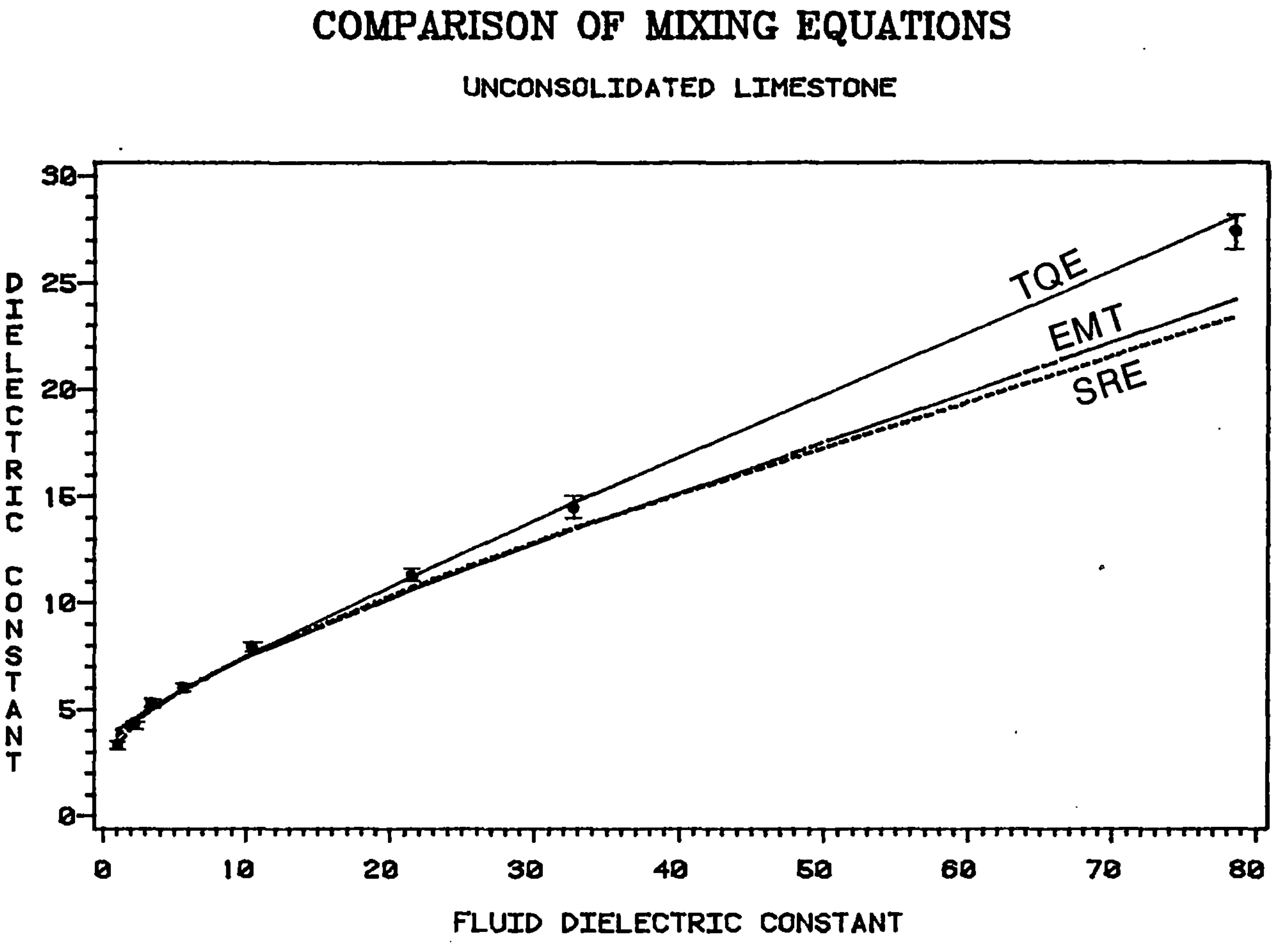


Figure 24. The comparison between the mixing laws when a common value for ε_s is used for all mixing laws.

Water Saturation of porous media. The application of mixing laws to partially saturated systems needs to be extendedto include the presence of the third component. The mixture formula of SRE and TQE have a straight forward application to multicomponent systems (Cox and Meador, 1975). The general form which includes the S_w factor can be written as

$$\varepsilon = [S_w \phi \varepsilon_w{}^c + (1 - S_w) \phi \varepsilon_a{}^c + (1 - \phi)\varepsilon_s{}^c]^{1/c} \qquad (5.3)$$

This equation represents the dielectric relationship for a porous system composed of solid matrix, water and air. In contrast to equation 5.3, the application of EMT formula to a three-component system requires a two step calculation by first considering two of the three components, then including the effect of the third. For example, if ottawa sand is partially saturated with water, there are three procedures used to calculate its composite dielectric constant using the EMT relation, depending on the choice of the first two components. These three possibilities are calculated and compared with measures for ottawa sand, as shown in Figure 25. The first option considers finding the effective dielectric constant of air and water, then the solid (ottawa sand) is included to determine the composite dielectric constant of the system. This option is designated by (I) in Figure 25. The second option assumes water resides on the surface of the particles. The effective dielectric constant of ottawa sand and water is determined then the presence of air is considered to find the composite dielectric constant as reflected by curve II in Figure 25. Curve III shows the third and last possible combination by starting with the solid and air, then including the effect of water. In these calculations one has to be careful to use the correct porosity in the EMT formula. For the first step, the porosity has to be taken as the ratio of one of the two components to the volume of both. When the third component is included the porosity is then the ratio of its volume to the total volume. From Figure 25 it appears that curve III shows a closer agreement to the measured points in comparison with curves I and II. Thus, the third option was adopted in the calculation for the partial saturations. The agreement of this choice with experiment emphasizes the fact that EMT works best when the solid and air are considered first in the numerical evaluation and then the result is combined with the water component.

The measurements are extended to compare the mixing laws (for partially saturated systems) using different materials. The results are presented by plotting the dielectric constant as a function of water saturation level. The measurements are compared to SRE, TQE and EMT. In the case of ottawa sand, (Figure 26), EMT and SRE behave similarly when $S_w < .60$ and show high correlation with the measurements. As S_w increases the two curves deviate and the measurements get closer to the curve representing TQE. When $S_w = 1.0$ (full saturation) the measurements are in good agreement with TQE. For limestone (Figure 27), the same trend is exhibited which indicates that the change in the shape and dielectric constant of the particles do not alter the dielectric constant relationship. Only small differences between SRE and EMT were observed for seminole loam soil, (Figure 28), and Grainola Complex soil, (Figure 29). For all cases, the measured points become closer to TQE as S_w approaches unity.

The similar results obtained from SRE and EMT and the simpler calculation achieved by SRE give this expression an advantage in determining the composite dielectric constant of a partially saturated material. Another major advantage of SRE is the relative ease that it can be inverted to calculate water saturation of porous systems. For a three component system, SRE is written as

$$\sqrt{\varepsilon} = S_w\phi\sqrt{\varepsilon_w} + (1 - S_w)\phi\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s} \tag{5.4}$$

The inversion of Equation 5.4, assuming $\varepsilon = \varepsilon_m$, to determine S_w is

$$S_w = \frac{(\sqrt{\varepsilon_m} - \sqrt{\varepsilon_o})}{(\sqrt{\varepsilon_w} - \sqrt{\varepsilon_a})\phi} \tag{5.5}$$

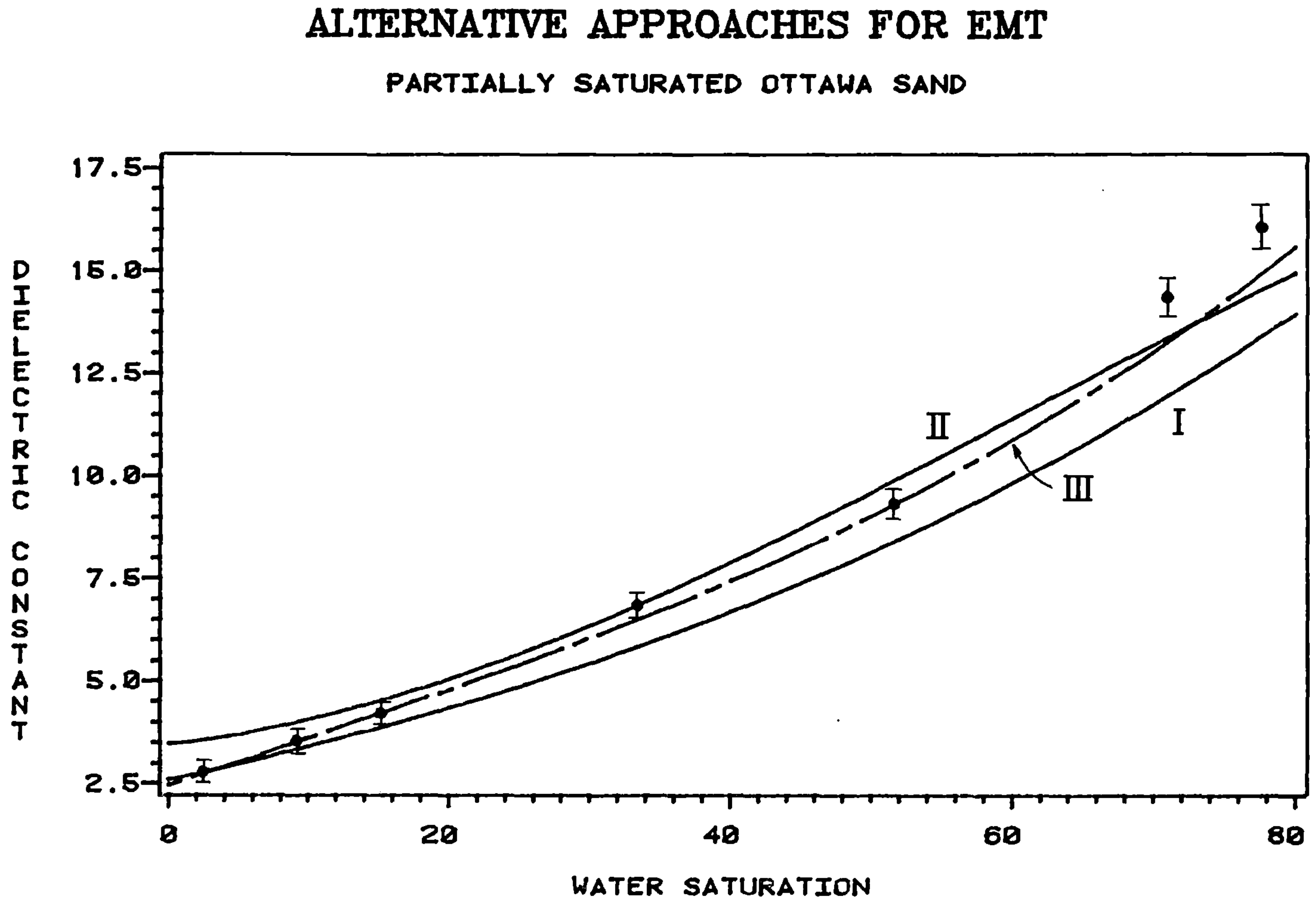


Figure 25. Option III (solid and air, then water) shows the closest agreement.

where ε_m is the measured dielectric constant of the system and $\sqrt{\varepsilon_o} = \phi\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s}$ is the composite dielectric constant for dry medium using SRE calculations. If the porous medium is saturated with water and another fluid, then the fluid saturation S_F is equal to $1-S_w$. The accuracy of Eq. 5.4 in fitting the measured results indicates the reliability of Eq. 5.5 in determing the partial saturation of water by inversion. Thus, the determination of S_w for porous media can be accurately determined from the knowledge of ε_s, ϕ, ε_o and ε_m.

Determination of water content. The water content θ_w, of a material is defined as the ratio of volume of water to the total volume of the medium. The dielectric measuring technique is applied to determine water content (θ_w) in the ensuing section. Particular emphasis is placed on measuring collected soil samples and developing a simplified inversion procedure to determine the water content from measurements of the dielectric constant.

Measurements for different samples are presented by plotting the measured dielectric constant (ε_m) vs. the water content (θ_w). Four types of soils are used in the measurements. These soils are seminole loam, Figure 30, and Grainola-Lucian Complex, Figure 31. Only small differences between EMT and SRE curves and the measured results are observed in the two Figures. Because the two mixing laws give essentially the same results, the simpler form of the SRE will be adopted in the ensuing paragraphs.

Application of this mixing law (SRE) to field measurements of composite dielectric constant is directed to determining the water content. The relationship between water saturation S_w, and water content is given by

$$\theta_w = S_w\phi \tag{5.6}$$

Using this relationship in the SRE (Equation 5.4) to obtain the water content yields

$$\theta_w = \frac{\sqrt{\varepsilon_m} - [\phi\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s}]}{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_a}} \tag{5.7}$$

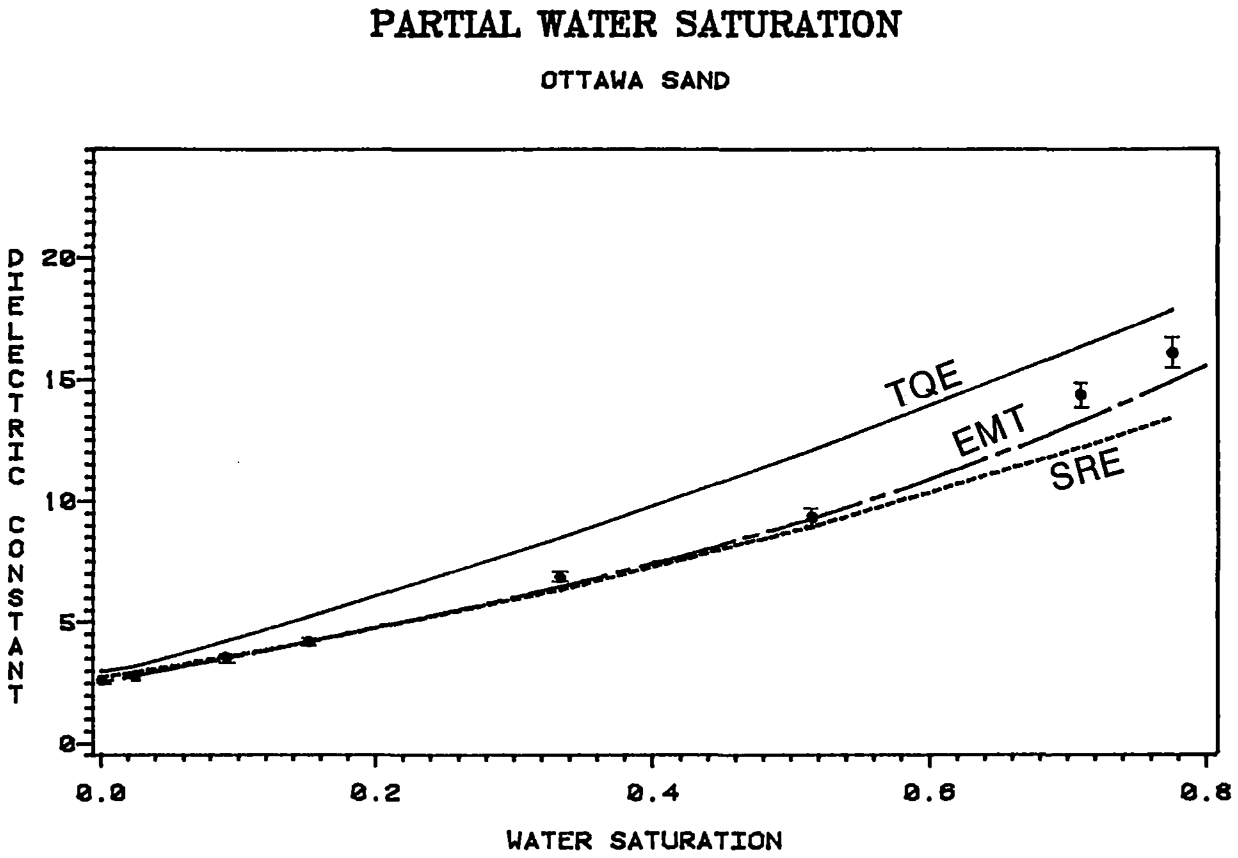


Figure 26. EMT and SRE show similar behavior up to 60% then they deviate and measured values get closer to TQE.

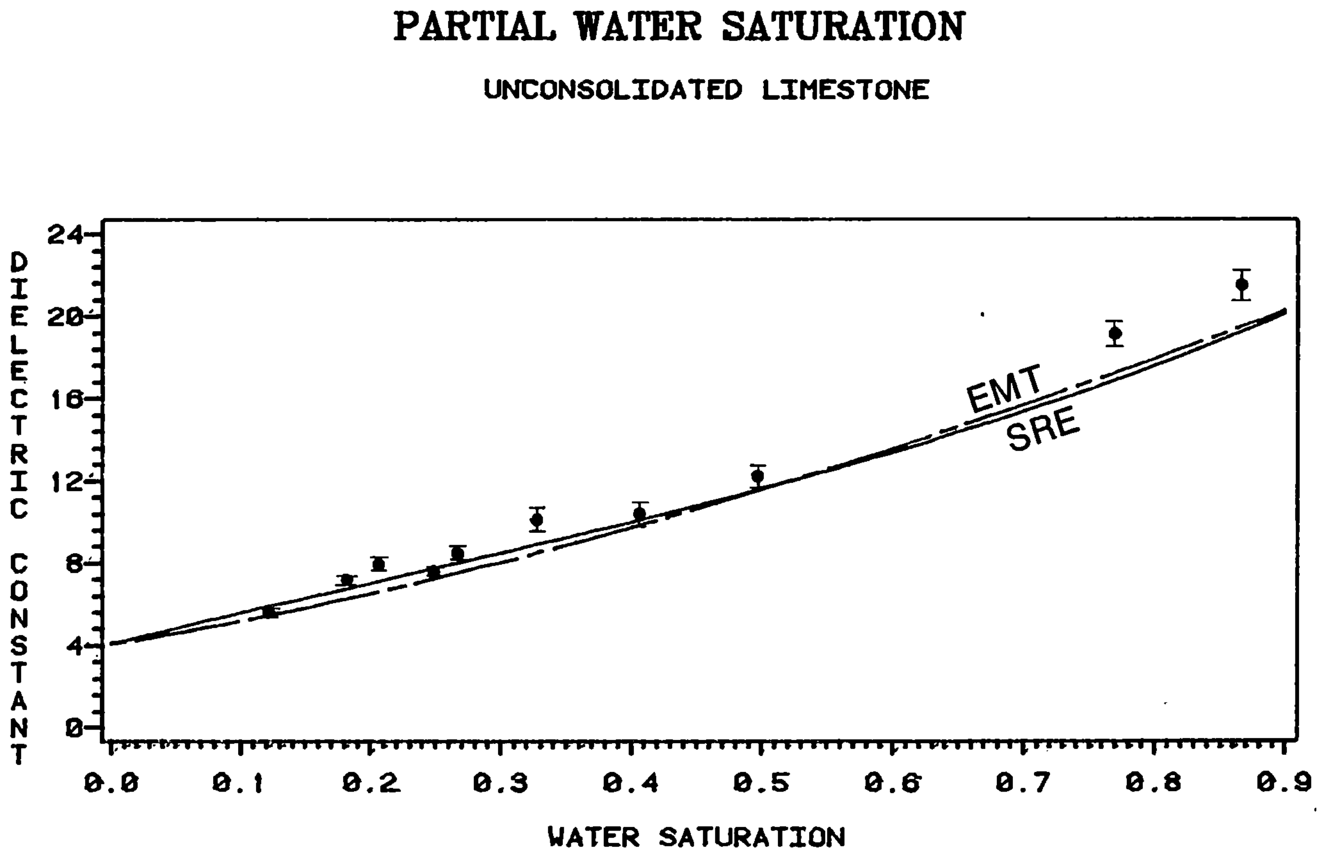


Figure 27. Close agreement between EMT and SRE for partially saturated limestone.

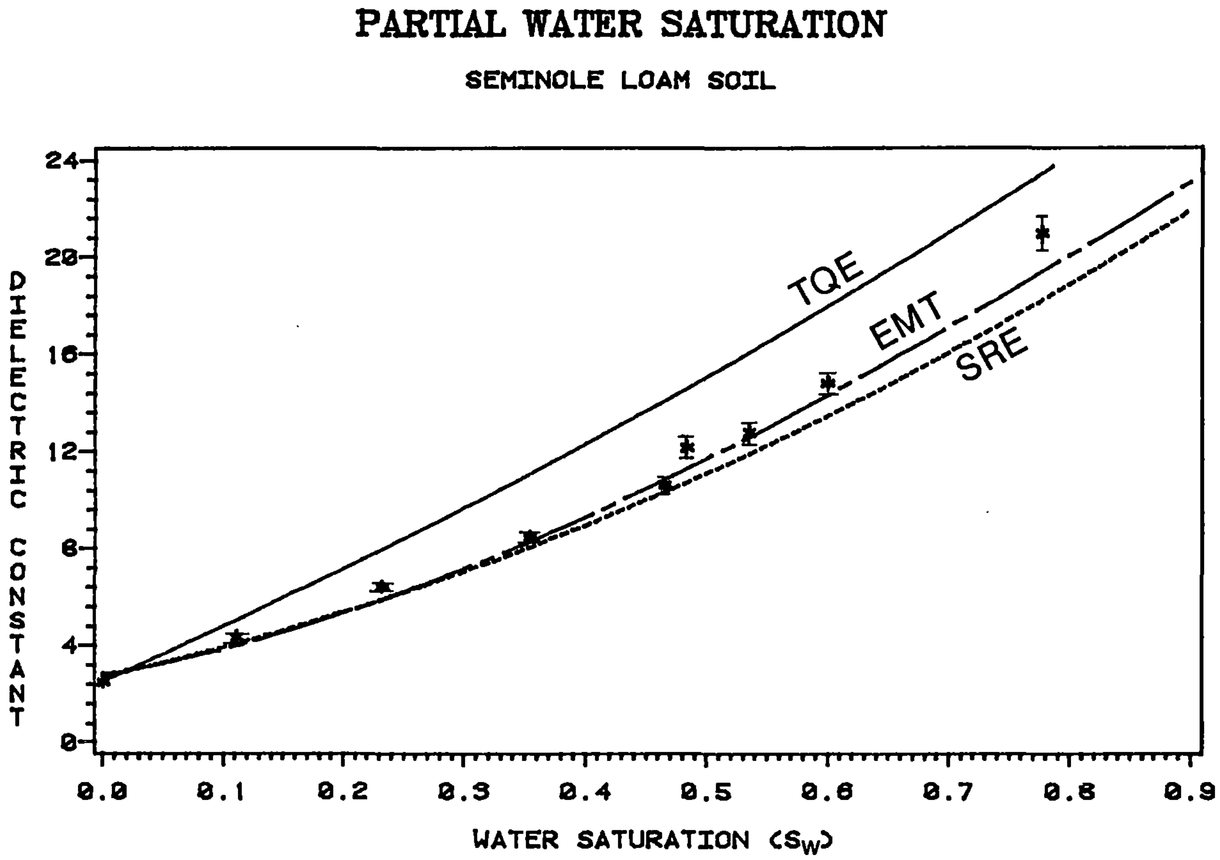


Figure 28. EMT and SRE show good agreement with measurements up to 60% saturation after which measured values approach the TQE curve.

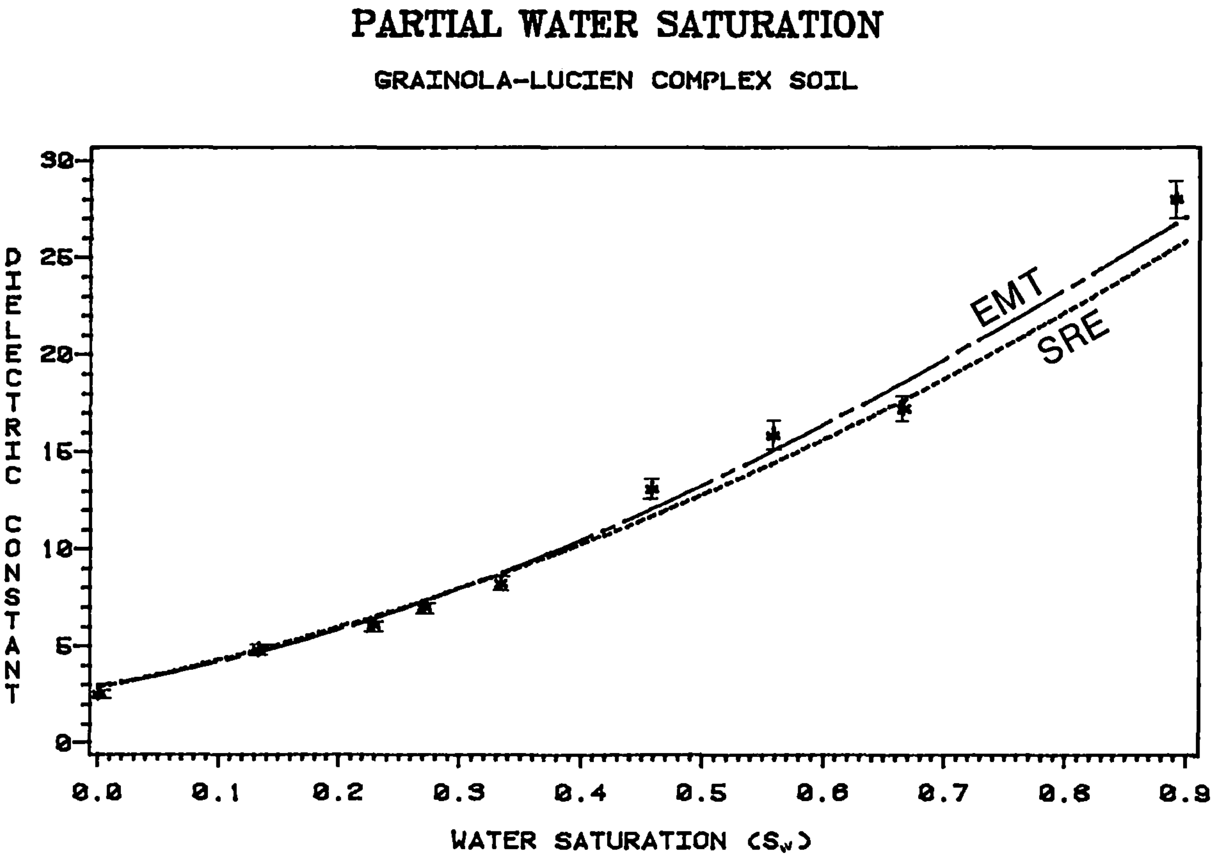


Figure 29. Same as in Figure 28 for another soil.

Where ε_m is the measured dielctric constant for the medium, ε_w and ε_a are the known values of dielectric constant for water and air, respectively. This equation is simplified considerably if it is assumed that SRE is also applied for dry measurement. Thus, Equation 5.7 becomes

$$\theta_w = \frac{\sqrt{\varepsilon_m} - \sqrt{\varepsilon_o}}{7.82} \tag{5.8}$$

where $\sqrt{\varepsilon_o} = \phi\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s}$ is the SRE value for the dry sample. Equation 5.8 does not require measurements of the porosity but does require two dielectric measurements of first, the partially saturated, and second, the air dry soil.

This expression could be simplified further since the value of ε_o is typically small and does not vary substantially within soil types. The composite dielectric constants for air saturated samples are shown in Table V to vary over a narrow range of values. If the general type of the medium can be identified, an average approximate value for the air saturated composite dielectric constant ($<\sqrt{\varepsilon_o}>$) could be chosen from a predetermined list, thus eliminating the need for a second measurement. The water content can then be obtained from the measurment of water saturated sample as

$$\theta_w = \frac{\sqrt{\varepsilon_m} - A}{7.83} = 0.128\ (\sqrt{\varepsilon_m} - A) \tag{5.9}$$

Where A is the square root term ($<\sqrt{\varepsilon_o}>$) chosen for that particular soil type. This Average Water Content (AWC) form provides a basis for determining water content from a single measurement of the moist soils composite dielectric constant while still including information about the average soil type through the parameter A.

This simplified approach (AWC) is similar to that taken by (Top et al., 1980) to describe the average dielectric properties of moist soils. An empirical formula is introduced

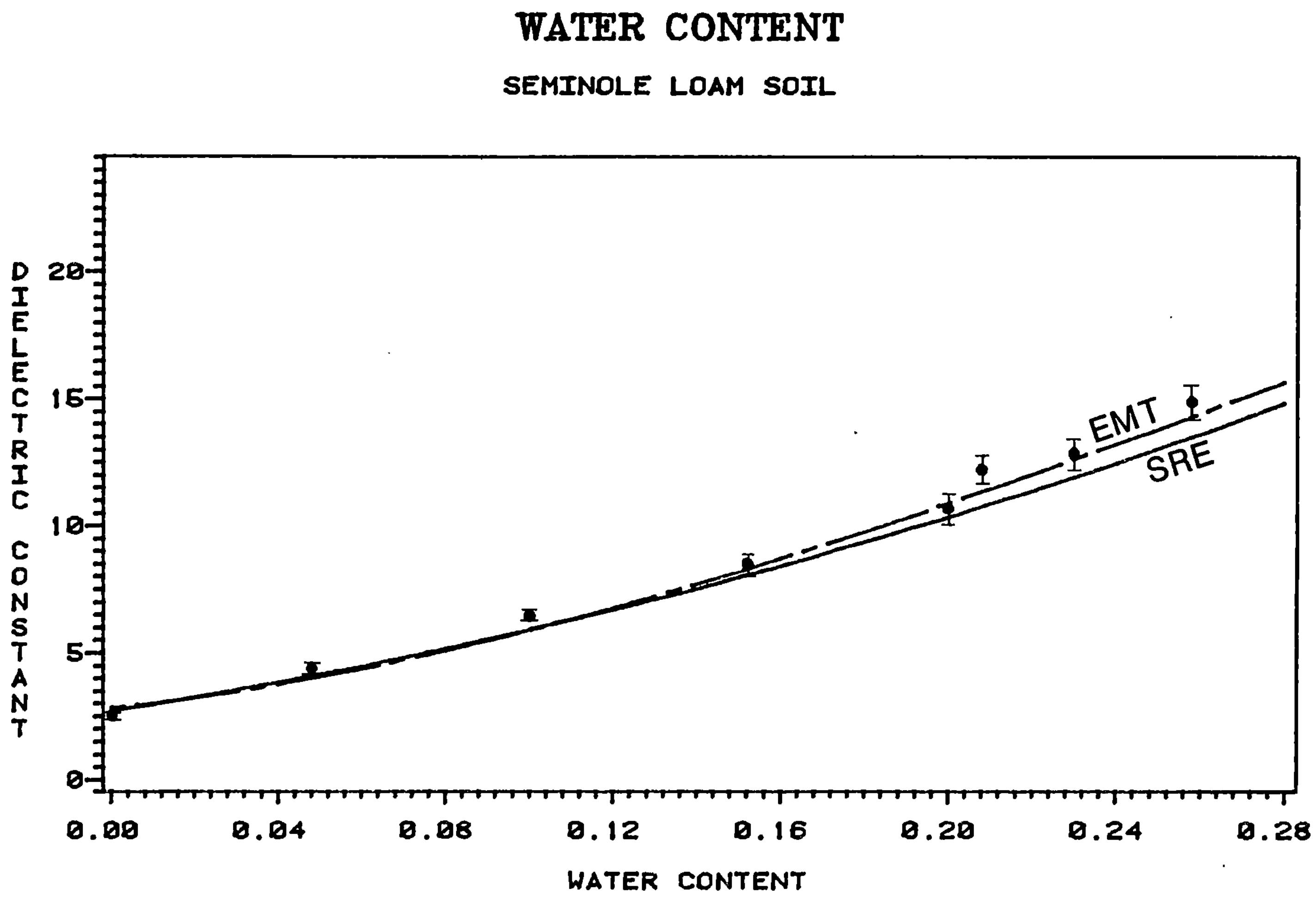


Figure 30. Close agreement for EMT and SRE with measurements up to 60% saturation (.25 water content).

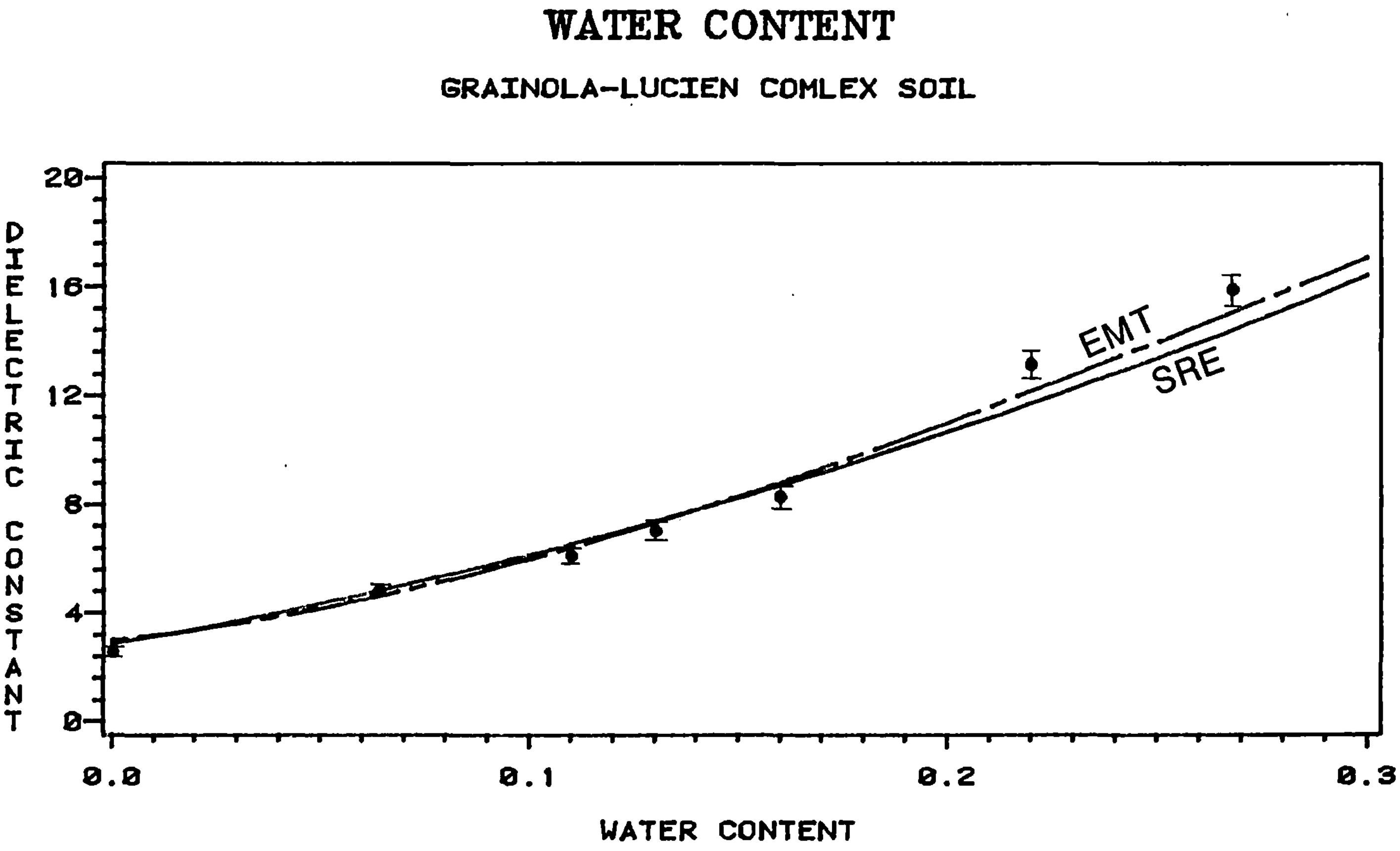


Figure 31. Close agreement for EMT and SRE with measurements up to 60% saturation (.28 water content).

TABLE V

THE VARIATION IN THE SQUARE ROOT OF THE DRY DIELECTRIC CONSTANT (A) FOR VARIOUS SOIL TYPES. THE PARAMETER A REFERS TO EQ. 5.9

Material	A
Seminole loam	1.57
Grainola-lucien	1.59
Bowie	1.62
Bates	1.53
Limestone	1.96

to serve as a universal expression which is independent of the soil properties. The formula is obtained by polynomial fit of data from a number of soils. The coefficients of the expansion do vary with soil type and the "average" fit chosen as

$$\varepsilon = 3.03 + 9.3\,\theta_w + 146.0\,\theta_w^2 - 76.7\,\theta_w^3 \qquad (5.10)$$

The inverting formula for Equation 5.13 is suggested using curve fitting, as

$$\theta_w = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\,\varepsilon_m - 5.5 \times 10^{-4}\,\varepsilon_m^2 + 4.3 \times 10^{-6}\,\varepsilon_m^3 \qquad (5.11)$$

The AWC (Equation 5.9) has the advantage over Equation 5.14 of including average information concerning the soil type.

A comparison of Equation 5.9 and Equation 5.11 with measured dielectric constant for a crushed limestone (Figure 32) shows that relation 5.9 provides a better fit to the measurements since it can account for average properties of the medium. Where more typical sand soils are considered, both Equation 5.9 and Equation 5.11 fit the result equally well as shown in Figure 32. At higher water contents the wetness is related to the measured composite dielectric constant by

$$\theta = .011\varepsilon_c + .32/A^3 \qquad (5.12)$$

which describes wetness for water saturations above 60%. This expression is determined empirically by fitting the observed data at large water saturations.

These two relationships (Eq. 5.9 and 5.12) offer a means of determining water content over the entire water saturation range of the soil. The procedure used to determine which of the two equations applies to the measurement uses the relation which provides the smallest value for the water content. This procedure is necessary since the water saturation range is seldom known in field measurements. Which AWC equation (5.9 or 5.12) should be applied to the measured results is given by the equation which yields the minimum value for the water content using the observed composite dielectric constant.

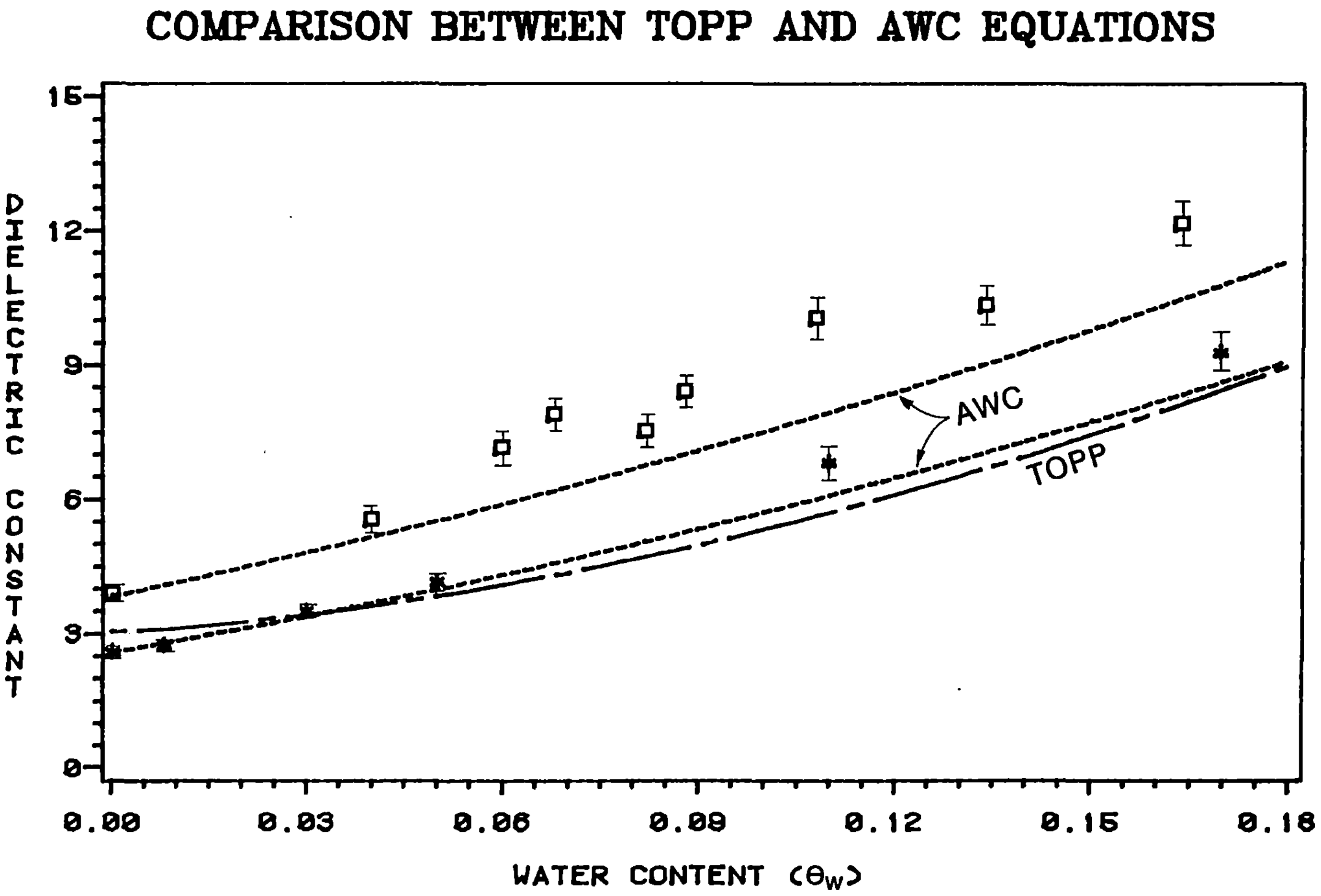


Figure 32. Squares represent measured values for limestone where the stars refer to ottawa sand.

Comparisons of the AWC expressions with the measured results are shown in Figure 33 for the entire wetness range (S_w to 100%). The measured results for the sandy soil agree with those obtained by Hoektra and Delaney (1974) using a TDR technique. The values used to obtain the dashed curves are the minimum wetness values obtained from either Equation 5.9 or 5.12. There is close agreement between the values of wetness measured at each observed dielectric constant and the AWC relations. The results from the "average" soil water content expression of Topp et. al is consistent with the measured results in the sandy soil at low water content, but is out of their specified uncertainty range at higher water content (S_w>60%).

However, the dashed curves constructed from the AWC equations are in close agreement with the measurements over the entire wetness range. This comparison indicates the versatility and accuracy of the AWC expression of Eqs. 5.9 and 5.12.

The AWC equation provides a concise form to rapidly evaluate field measurements using known average characteristics of the soils. The one step measurement process offers a simple and accurate relationship between the measured dielctric constant and the water content which allows prompt field evaluation.

Multiple Fluids Saturation

The previous discussion dealt with materials which contain one or two fluids filling the pores. In actual reservoirs, three fluids (or more) could be saturating the medium. In this case, the mixing laws become more complicated. The only practical mixing law which can be used to calculate the composite dielectric constant is the empirical formula (Equation 4.17). If the material consists of water, oil and the solid, then the mixing law becomes

$$\varepsilon = [S_w\phi\varepsilon^c_w + S_o\phi\varepsilon^c_o + S_a\phi\varepsilon^c_a + (1 - \phi)\varepsilon^c_s\,]^{1/c} \qquad (5.13)$$

Where S_w, S_o and S_a are the ratios of the water, oil and air to the pore volumes, such that,

APPLICATION OF AWC EQUATIONS

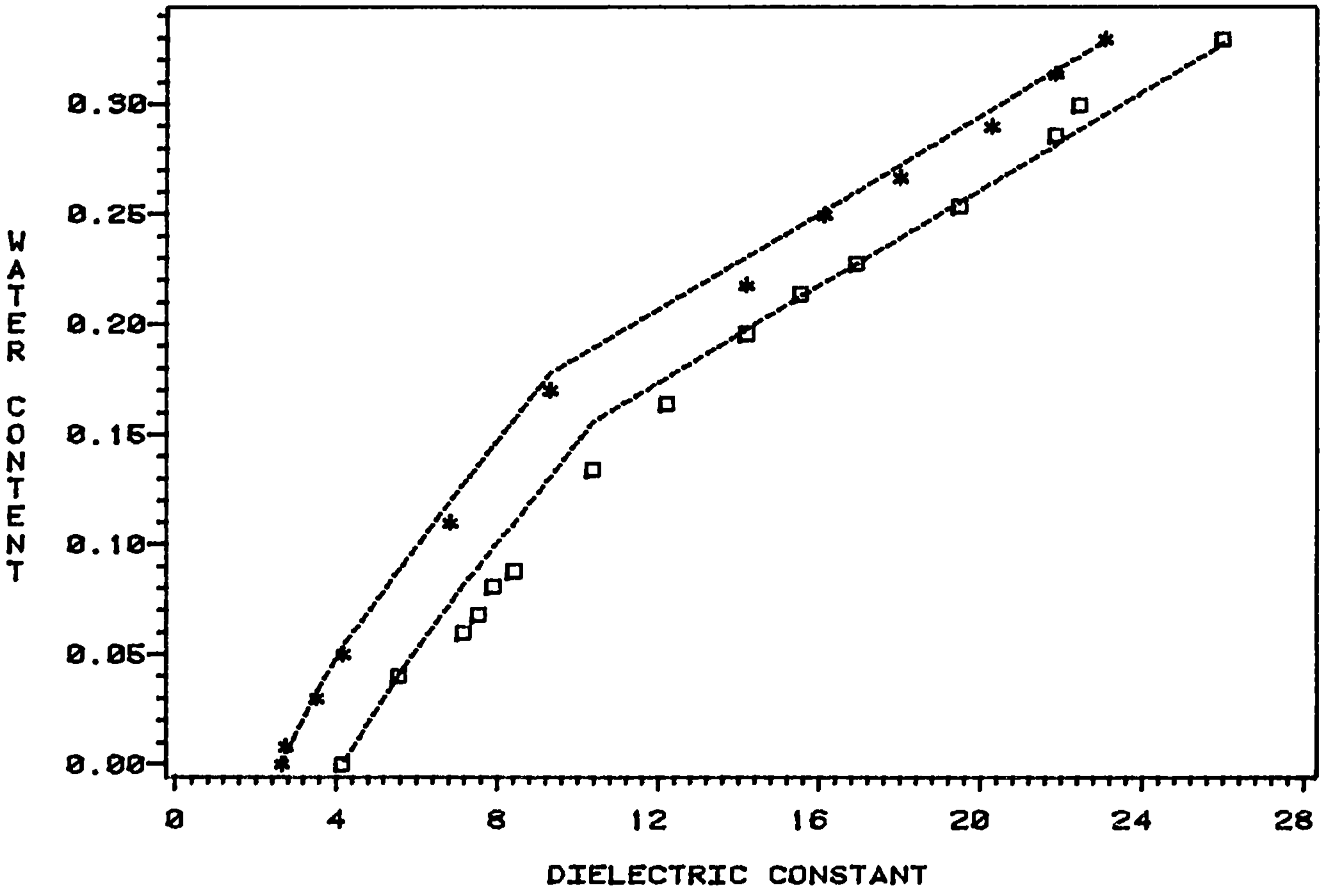


Figure 33. The curves represent AWC expressions as compared to limestone (squares) and ottawa sand (asterisks).

TABLE VI

OTTAWA SAND SATURATED WITH THREE DIFFERENT FLUIDS, WATER, CRUDE OIL, AND AIR. ε IS THE MEASURED WHILE SRE REPRESENTS THE CALCUALTED VALUES FROM SRE MIXING LAW. $S_a + S_o + S_w = 1$

S_a	S_o	S_w	ε	SRE
.788	.212	0	2.97	2.83
.745	.139	.115	3.63	3.84
.745	.145	.109	3.80	3.82
.781	.127	.091	3.63	3.62
.806	.127	.067	3.54	3.39
.867	.079	.054	3.37	3.25

TABLE VII

UNCONSOLIDATED SANDSTONE WITH THE FLUIDS, (WATER, CRUDE OIL AND AIR)

S_a	S_o	S_w	ε_m	SRE
.112	.888	0.0	3.13	2.97
.130	.856	.014	3.29	3.46
.103	.846	.051	3.98	3.93
.182	.777	.042	3.81	4.17
.260	.698	.042	3.63	3.70
.227	.698	.0744	3.98	4.13
.377	.545	.0744	3.63	4.01
.386	.516	.097	4.55	4.65
.433	.479	.088	3.98	4.15
.415	.464	.116	4.17	4.48
.395	.423	.181	5.78	5.49
.469	.40	.130	5.14	4.69
.326	.40	.274	8.16	7.04
.275	.40	.325	8.96	7.98

$$S_w + S_o + S_a = \frac{V_w + V_o + V_a}{V_p} = 1$$

The EMT formula is excluded because of the complexity in determining the composite dielectric constant with different combinations of the constituents.

Preliminary measurements have been done on ottawa sand and sandstone saturated with air, crude oil and water. Equation 5.16 can be written for SRE as

$$\sqrt{\varepsilon} = [S_w\phi\sqrt{\varepsilon_w} + S_o\phi\sqrt{\varepsilon_o} + (1 - S_a\phi\sqrt{\varepsilon_a} + (1 - \phi)\sqrt{\varepsilon_s}] \qquad (5.14)$$

where $S_a = 1 - (S_w + S_o)$. Measurements have been compared with calculated values for Equation 5.14 and for ottawa sand and sandstone. The agreement is satisfactory, as presented in Table VI and VII.

The parameters of interest in these combinations are S_w and S_o. If the material is assumed to have a solid dielectric constant of 4.5 and porosity of .37, a surface plot of $\sqrt{\varepsilon_e}$ vs. S_w and S_o is shown in Figure 34. In the Figure it is assumed that S_w ranges from 0.0 to .20 while S_o for 0.0 to 0.80. If either $S_w$or S_o is known the other can be determined directly from the surface figure with the knowledge of composite dielectric constants. If the crude oil is replaced by methanol for the same medium, the behavior of ε is shown in Figure 35.

Thus, to determine ε_s for a porous medium, the EMT mixing law is used with the measured dielectric constant of the dry sample. This value of ε_s is applied with all mixing laws to determine the composite dielectric constant (ε). For porous media saturated with fluids of high dielectric constant (water in particular) the dielectric constant can be calculated using TQE whereas with low dielectric constant fluids the dielectric constant is obtained from EMT. For partially saturated porous media SRE shows satisfactory results in finding the dielectric constant and in the inverse calculation of water saturation (S_w), the water content of the soil can be determined from the simplified AWC expressions.

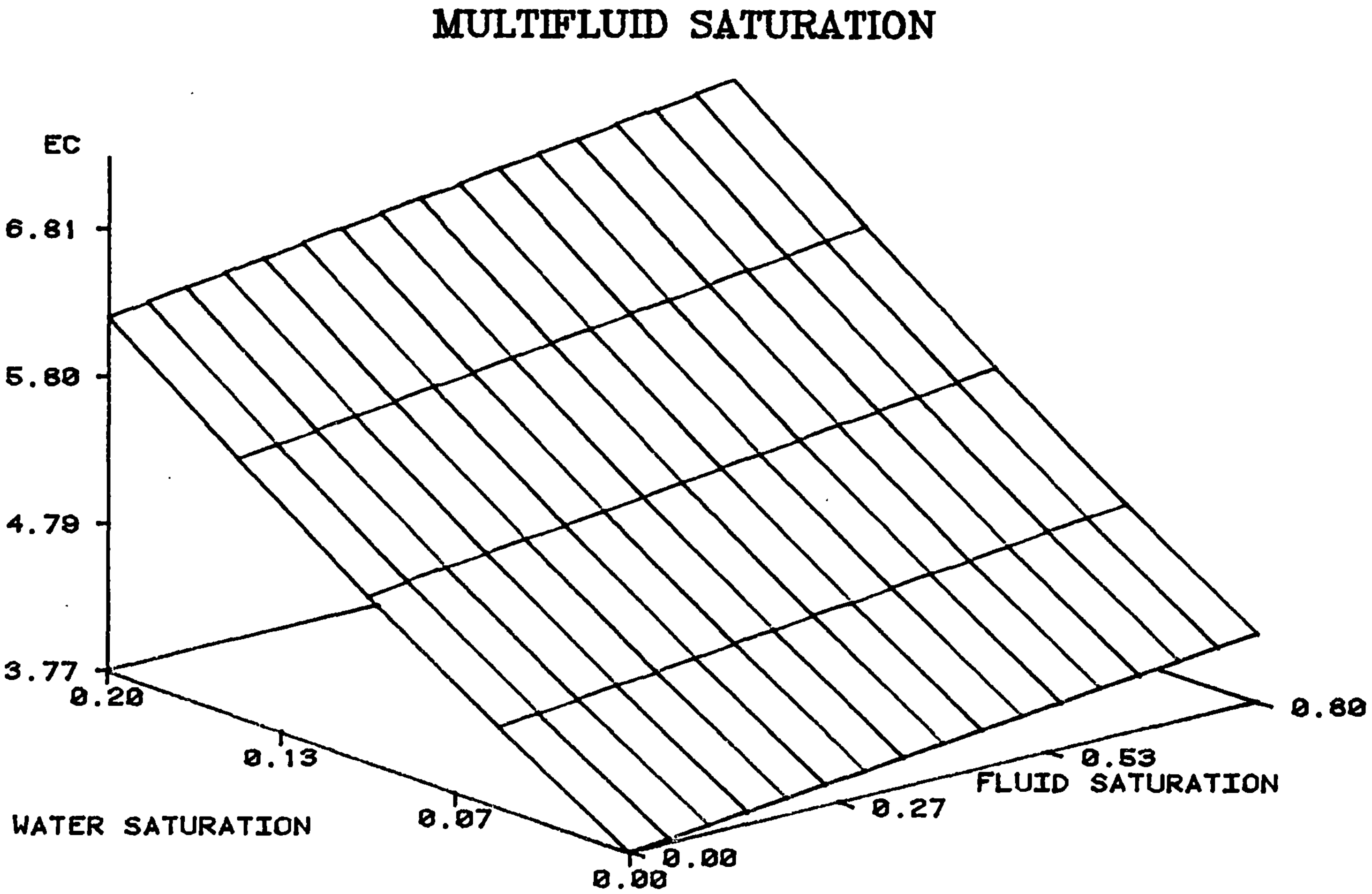


Figure 34. A surface plot for calculated dielectric constant of a porous medium saturated with air, crude oil and water.

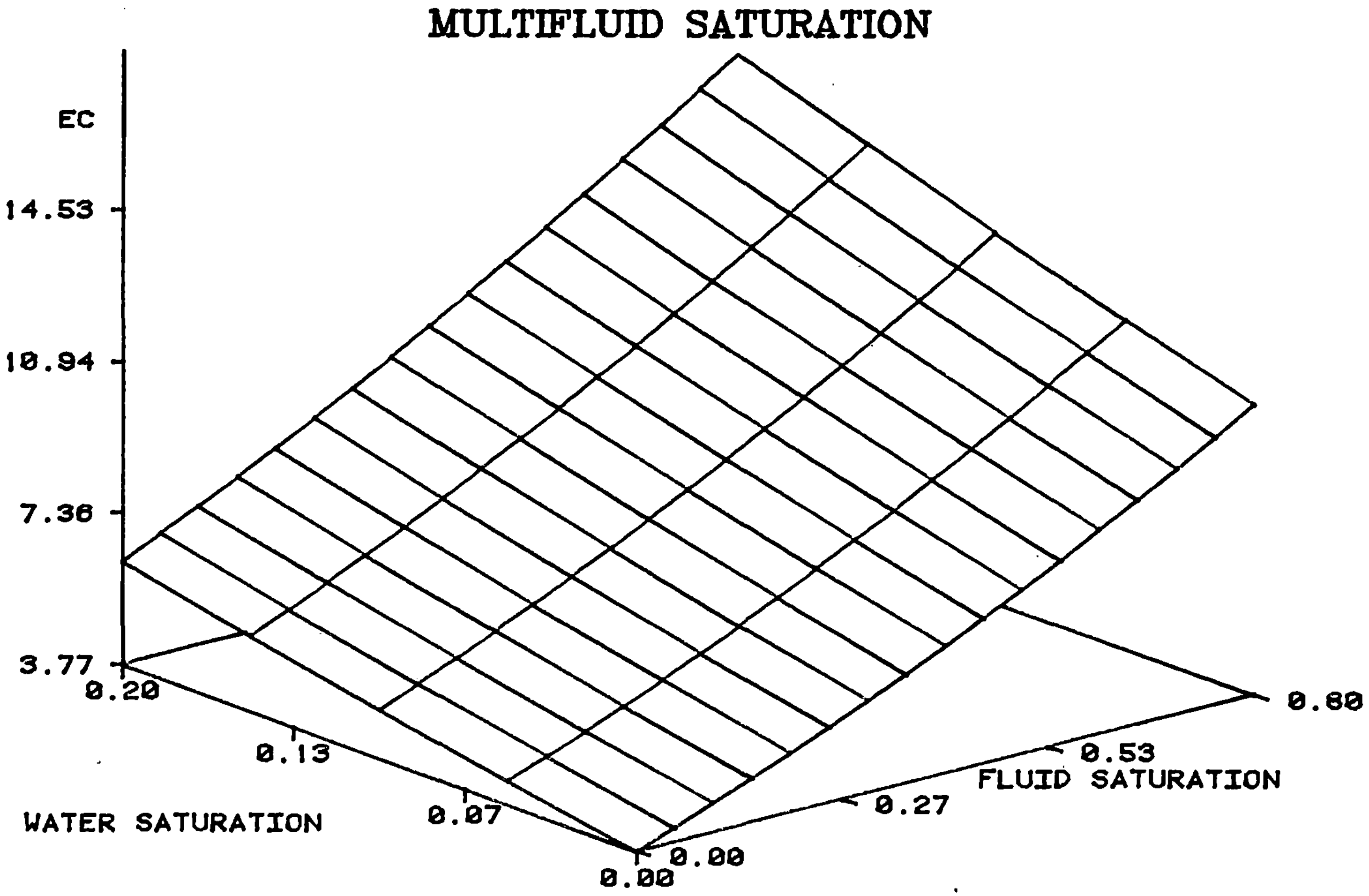


Figure 35. A surface plot for calculated dielectric constant of a porous medium saturated with air, methanol and water.

Dielectric Constant of Emulsions and Solutions

The test of the validity and applicability of mixing laws is extended to include the dielectric measurements of two types of emulsions and three different solutions, each of two miscible liquids. The emulsions used are oil-in-water (o/w) emulsions where the oil is represented by carbontetrachloride in one case and by crude oil in the other. These two "oils" have contrasting viscosities which result in forming two different emulsions. The solutions, on the other hand, include three combinations encompassing different ranges of dielectric constant. The calculated composite dielectric constant of these emulsions and solutions obtained using the mixing laws SRE, TQE, VFE and EMT are compared with the measured values.

The preliminary study presented here concentrates on the o/w emulsion. The oil droplets form the dispersed phase while the water is the continuous phase. For the three mixing laws, (SRE, TQE and VFE) no assumptions about the configuration are made because it is equivalent to consider either of the two emulsion components as dispersed in the other. In contrast, for EMT it is assumed (as was the real case) that oil is dispersed in the water. It is interesting to note that the inversion of application of the EMT could lead to erratic results. For example, if 50% of crude oil in 50% of water is considered as o/w, its composite dielectric constant is 29.68 while for w/o it has the value of 11.08.

The measured dielectric constant is plotted as a function of oil concentration for various emulsions. At very low concentrations (up to 5%) the calculated values are similar for all mixing laws because in this situation water with its high dielectric constant is dominating the expression and the gradual change in the amount of oil causes only a slight change in the measured and the calculated dielectric constants. At such concentrations the oil droplets are widely separated and their interaction is limited.

For high concentrations of crude oil in water (Figure 36), the measured dielectric constants are plotted along with calculated values of composite dielectric constant using the SRE, TQE and EMT. The VFE is excluded because it was found to have extremely higher values at all ranges of concentrations used. The maximum concentration of crude oil in water is 60%. A comparison of the measured results and mixing laws in Figure 36 shows that the EMT is in good agreement with the measurements, particularly for oil concentrations above 5% where other mixing laws deviated from the observations. This result is not surprising since the derivation of the EMT assumes the dispersion of one of the systems into the other (Hasted, 1973). For carbontetrachloride in water emulsion (Figure 37), the maximum concentration achieved was only 25%, above which the two immiscible liquids became totally separate. The same discussion of Figure 36 applies for Figure 37. In a separate experimental set up using photocell and light scattering, it was found that for low crude oil concentrations (2%) the transport of oil droplets was very slow which indicates the stability of the emulsion. The dielectric constant measurements were made when the coaxial transmission line was in the vertical position. The transmission line was left out for a few days and measured again. There was no change in the dielectric constant which indicates that even if there were some coalesence of the oil droplets at the top of the line, the change in the measurements was negligible. On the other hand, when the coaxial line was placed horizontally, a change in the behavior of the measured dielectric constant was observed. The measured dielectric constant increases as a function of time. Such increase can be accounted for by the oil droplets settling to the bottom of the waveguide resulting in the center conductor being surrounded by water, instead of o/w emulsion. The mathematical treatment of the EM wave propagation is complex since the cross section of the medium surrounding the center conductor is not uniform and the lowest order TEM modes will not propagate.

The dielectric measurements on three solutions were also compared to the mixing laws. The first solution consists of two nonpolar fluids (cyclohexane and crude oil). Since the cyclohexane and crude oil have identical dielectric constant (2.02) the relative mixture of both produces a constant dielectric constant as a function of the component fractions. This solution measurement was intended to determine whether any alternation of the composite

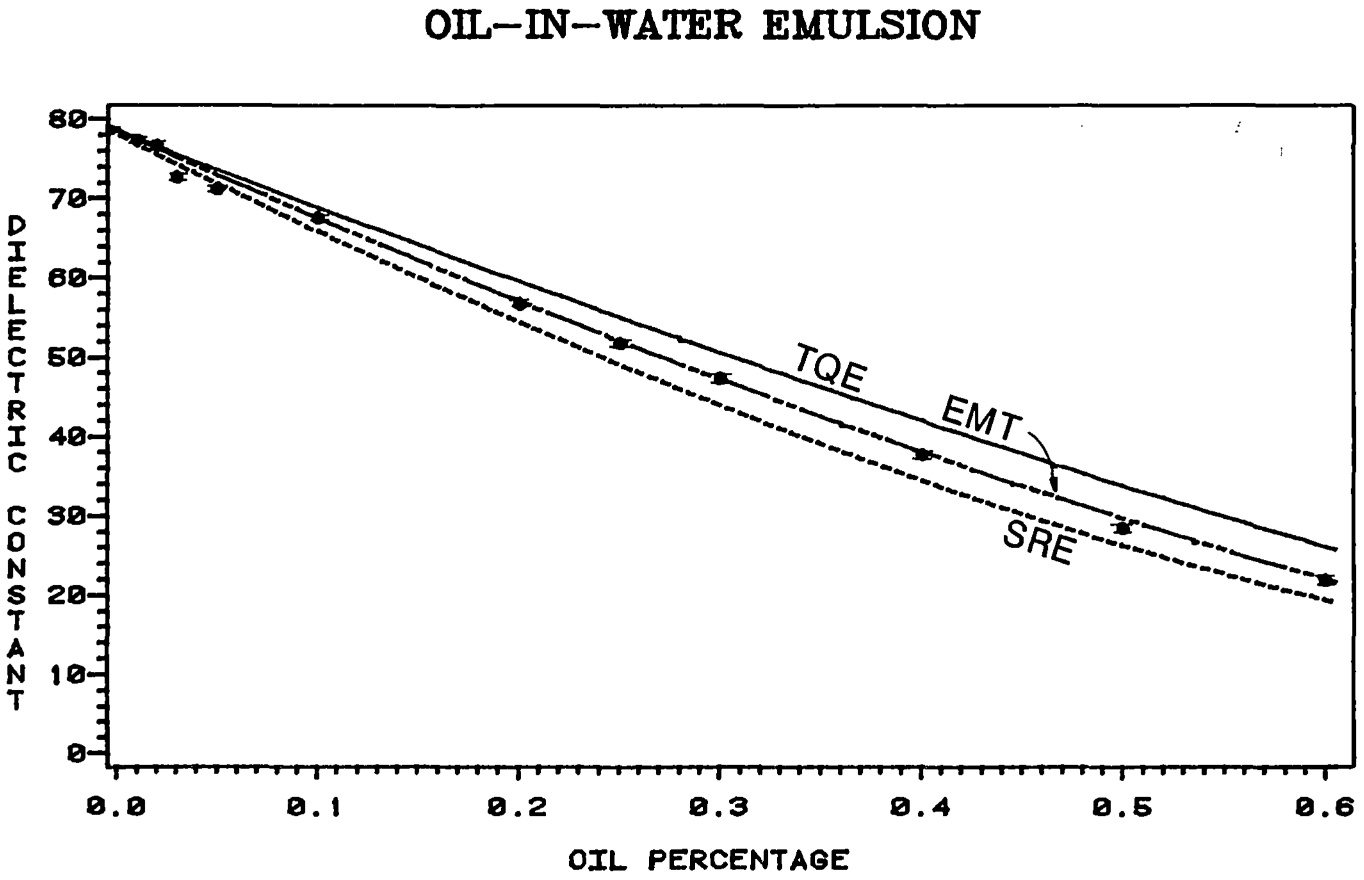


Figure 36. Comparison of the measured (dots) to the calculated dielectric constants. Crude oil is the dispersed phase.

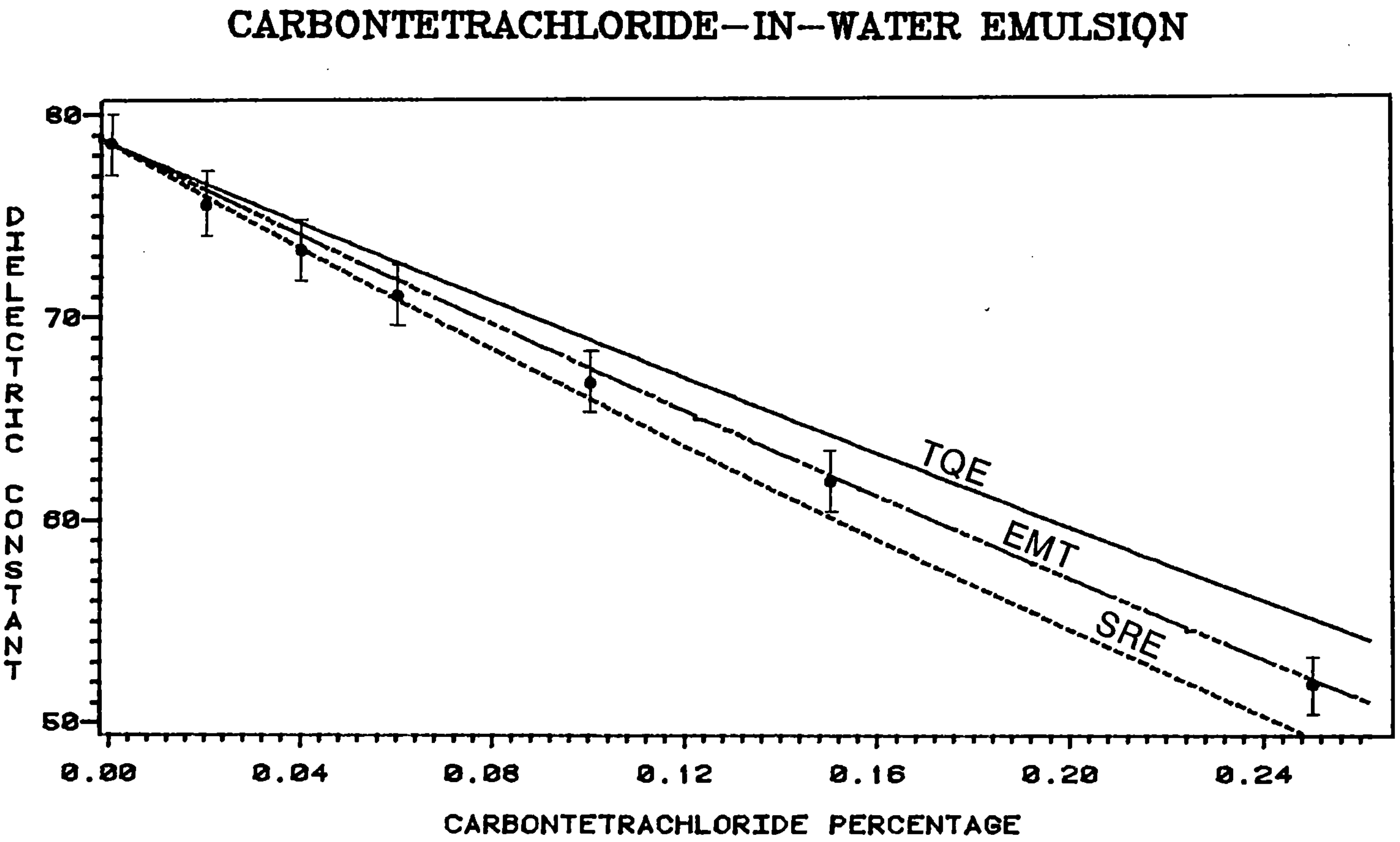


Figure 37. Comparison of the measured (dots) to the calculated dielectric constants. Carbontetrachloride is the dispersed phase.

dielectric constant occurs due to microscopic mixing. The second solution type consists of two polar fluids (methanol and water). The discussion concerning the solution of non-electrolyte polar organic fluid and water (Hasted, 1973) predicted that the composite dielectric constant calculated from mixing laws would not be in agreement with the measurements. Figure 38 shows that the measured values are greater than the upper extreme of the calculated dielectirc constant determined from the mixing law, i.e. VFE. This means that the solution of methanol and water produces a "new" compound whose dielectric constant can not be explained except by an empirical formula. The best fit is achieved by using the exponent $c = 1.5$ in Eq. 4.17. The highly hydrophilic property of methanol could be responsible for such characteristics. The final solution was made by crude oil (nonpolar) and 1,2 dichloroethane (weak polar) and the results are shown in Figure 39. Since the difference in the dielectric constant of the two fluids is relatively small, all mixing laws applied show little difference among themselves, particularly at both low (10%) and high (90%) concentrations. All the measured composite dielectric constants fall below the mixing laws, which is in contrast to the solution of two polar fluids (Figure 38). The structure of the solute-solvent combination suggests a mechanism to explain their diverse dielectric behavior. In the first case (methanol/water solution), water with its high dipole moment and consequently high dielectric constant may interact on a molecular level with methanol and tend to align their respective dipole moments in the same direction. In the second case (crude/dichloroethane oil) the crude oil as a nonpolar fluid when mixed with dichloreothane may be reduced by the affect exerted by the dichloroethane weak polarity through chemical bonding behavior on a molecular interaction.

The measured results for the two fluid systems exhibit quite different behavior depending on whether the mixing is macroscopic (emulsions) or microscopic (solutions). The mixing laws are more sucessful in describing the experimental results for the emulsions than for the solutions.

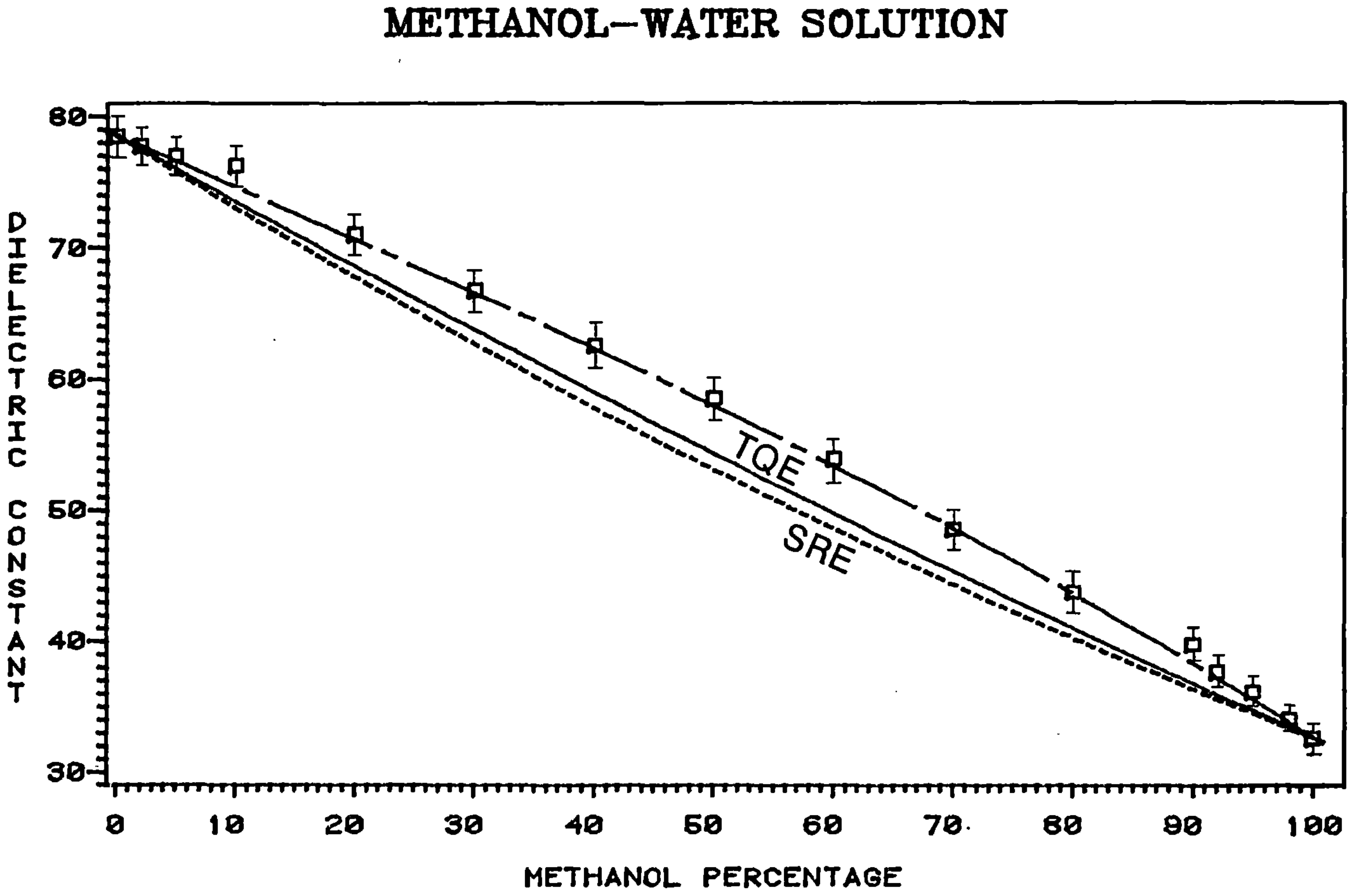
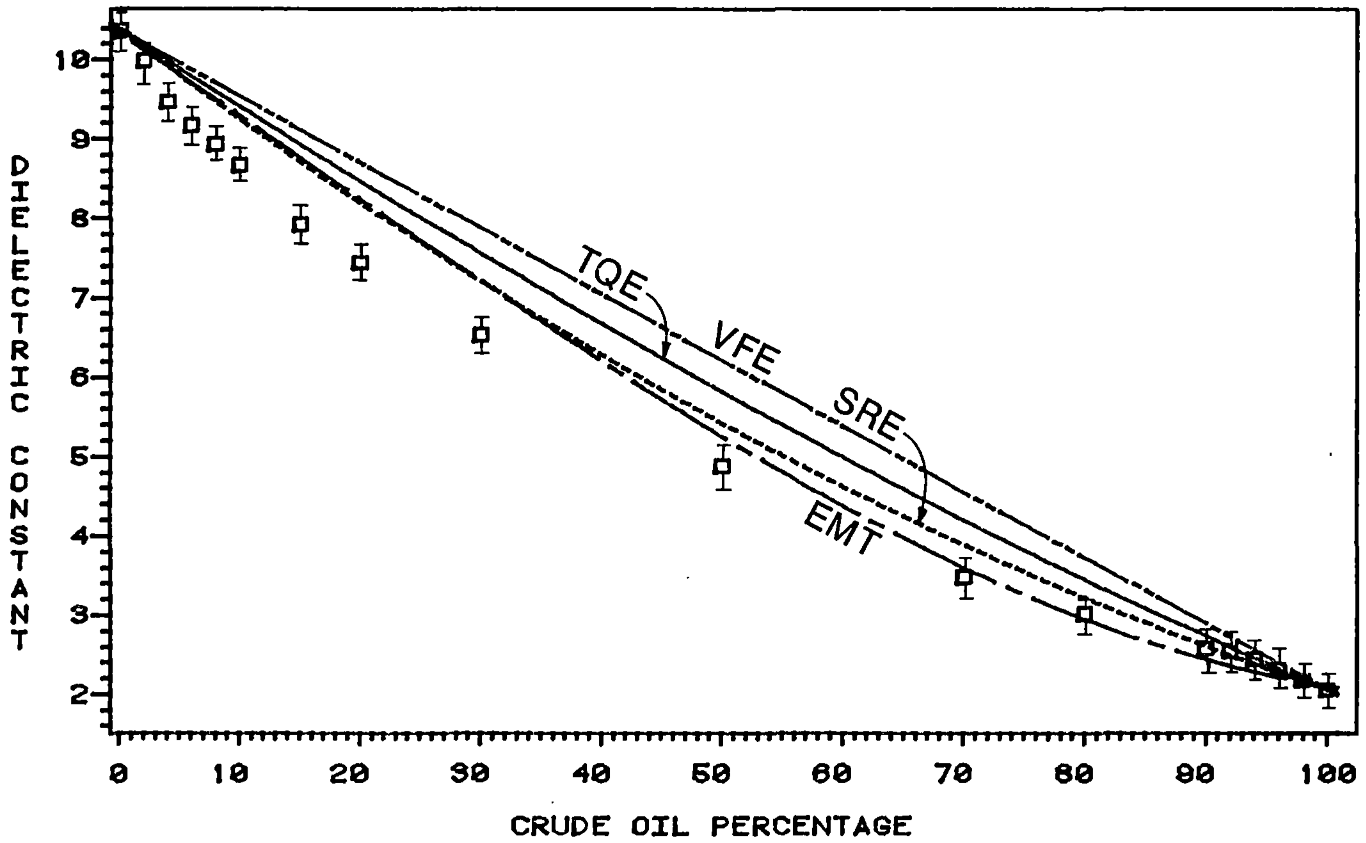


Figure 38. The curve which fits the measured data is the form of Eq. 4.17 with the exponent C = 1.5.



CRUDE OIL–DICHLOROETHANE SOLUTION

Figure 39. Measured values fall below the presented mixing laws for crude oil/dichlorethane solution.

Consolidated Materials

The measurements outlined in the previous section dealt with unconsolidated materials where parameters such as the porosity and the dielectric constant of the fluids and the solid (with their volume fractions) were needed to calculate the compsote dielectric constant to compare to the measured results. When geological samples are taken from oil wells they are generally in a consolidated state. They are kept as core pieces to preserve their natural characteristics. To perform the measurements the cores are cut into cylindrical rods and encased in the coaxial line which operates as a sample holder. The procedure for determination of dielectric constants for such cores requires additional steps to evaluate the composite dielectric constant because the consolidated materials do not completely fill the coaxial line. Rather, there are gaps between the inner conductor of the coaxial line and the inner diameter of the core sample (Chapter III). Additional parameters are needed to evaluate the measured values and obtain the dielectric constant of the core materials. These include i) the diameters of the inner and outer conductors of the coaxial line, ii) the inner and outer diameter of the cone sample and iii) the dielectirc constant of the fluid filling the gaps. In the following sections the effect of these factors and how the dielectric constant of cores can be determined from measured values will be discussed.

The Correction Formula and Gap Effect

When a core sample is machined to fit the coaxial line there is an inherent gap between the coaxial line conductors and the sample which can be a major source of error unless proper precautions are taken. The effect of the gap can be compensated for by the use of a correction equation which relates the measured dielectric constant to the parameters of the sample and the coaxial line, the size of the gaps, and the fluid surrounding the sample. The dielectric constant of the core material can be obtained using a procedure which compensates for the gaps and excess fluids. This correction equation takes the form

TABLE VIII

COMPARISON BETWEEN MEASURED AND CALCULATED VALUES OF DIELECTRIC CONSTANT OF DIFFERENT RODS, WHEN A VERY TIGHT FIT BETWEEN INNER DIAMETERS IS USED.

A = 0.821mm, C = 8.25 mm, D = 8.27 mm. Air is used to fill the gap.

Rod Dielectric Constant	2b(mm)	measured (ε_m)	Calculated
10.0	0.850	6.63	8.92
12.0	0.875	6.98	8.97
16.0	0.889	8.41	10.53
20.0	0.850	8.92	13.44
25.0	0.875	11.18	15.49
30.0	0.875	9.737	17.20

$$\varepsilon = \frac{\ln(^{d}/a)}{^{1}/\varepsilon_{fg}\ln(^{b}/a) + 1/\varepsilon_{c}\ln(^{c}/b) + ^{1}/\varepsilon_{fg}\ln(^{d}/c)}$$

$$= \frac{\ln(^{d}/a)}{^{1}/\varepsilon_{c}\ln(^{c}/b) + ^{1}/\varepsilon_{fg}\ln(^{bd}/ca)} \qquad (5.15)$$

where ε_c is the dielectric constant of the core, ε_{fg} is the dielectric constant of the fluid in the gap, ε is the measured dielectric constant of the coaxial line and a, b, c, d, are the diameters of the conductors and the core. The purpose of the following section is to analyze the effect of the gap on the dielectric constant and how the composite dielectric constant of the sample can be obtained using the correction formula.

The effect of the gap was determined using solid (non-porous) dielectrics with known dielectric constant of 2.55 to 30.0. These dielectrics, which were obtained from Emerson and Cuming, Inc., were cut into cylinders to fit the coaxial line. Initial attempts were made to fabricate a very tight fit between the dielectric cylinders and the conductors of the coaxial line. The inner and outer diameters were designed to be equal (a = b, c = d to 1 part in 100). Since the gaps between the diameters are small, the measurements were made only when air is filling the gaps. Knowing all the required parameters, the correction equation was used to calculate the dielectric constant of the system. Table VIII shows a comparison between the measured and the calculated dielectric constant for six different cylinders. The inconsistency in the measured results shows that the measurements are very sensitive to the inner gap dimensions. Small irregularities in the trimmed surface of the sample and the center conductor are sufficient to introduce substantial deviation in the measurements from their calculated values. Therefore, an alternative approach is to eliminate this sensitivity by making the diameter of the sample measurably different from the conductor's diameter. The fluids used to surround the cylindrical specimens in these measurements are mainly air and water. Polystyrene was used to study the effect of the ratio (a/b) between the inner radius for the conductor to that of the cylinders on the measured dielectric constant. Figure 40 shows the behavior of the dielectric constant as a function of the ratio (a/b) when air is used to fill the gaps. The solid line represents the corrected values of the dielectric constant calculated from Equation 5.15 while the points represent the measured values. The figure shows that the deviation between the measured and the calculated dielectric constant increases as ratio (a/b) approaches unity and decreases when (a/b) is relatively large.

The determination of the dielectric constant of a core sample requires particular care when the samples are fabricated to fit a coaxial transmission line.

Application of Correction Equation to Standard Cylinders

Standard dielectric cylinders supplied by Emerson and Cuming, Inc. were used to test the applicability of the correction Equation 5.15 given above. The ration (a/b) is fixed at about .6 while the cylinder's dielectrics and the gap-fluid dielectric constant are changed for comparison. The results are analyzed as the dielectric constant for the cylinders is varied or as a function of the gap-fluid dielectric constant. The measured values are compared with those calcualted from Equation 5.15.

The dielectric constant as a function of the cylinders dielectric constant when air is filling the gap is shown in Figure 41. The points are the measured values while the solid line is the curve calculated form the correction equation. The figures show that disagreements between measurements and calculations increase as the cylinder's dielectric constant increases. This shows the sensitivity of the measurements to geometric parameters when the filling fluid is air. It also shows that the agreement is best when water is used to fill the gap for the same cylinders as shown in Figure 42. This is as a result of the term which includes ε_{fg} becoming very small when water fills the gap. In addition to

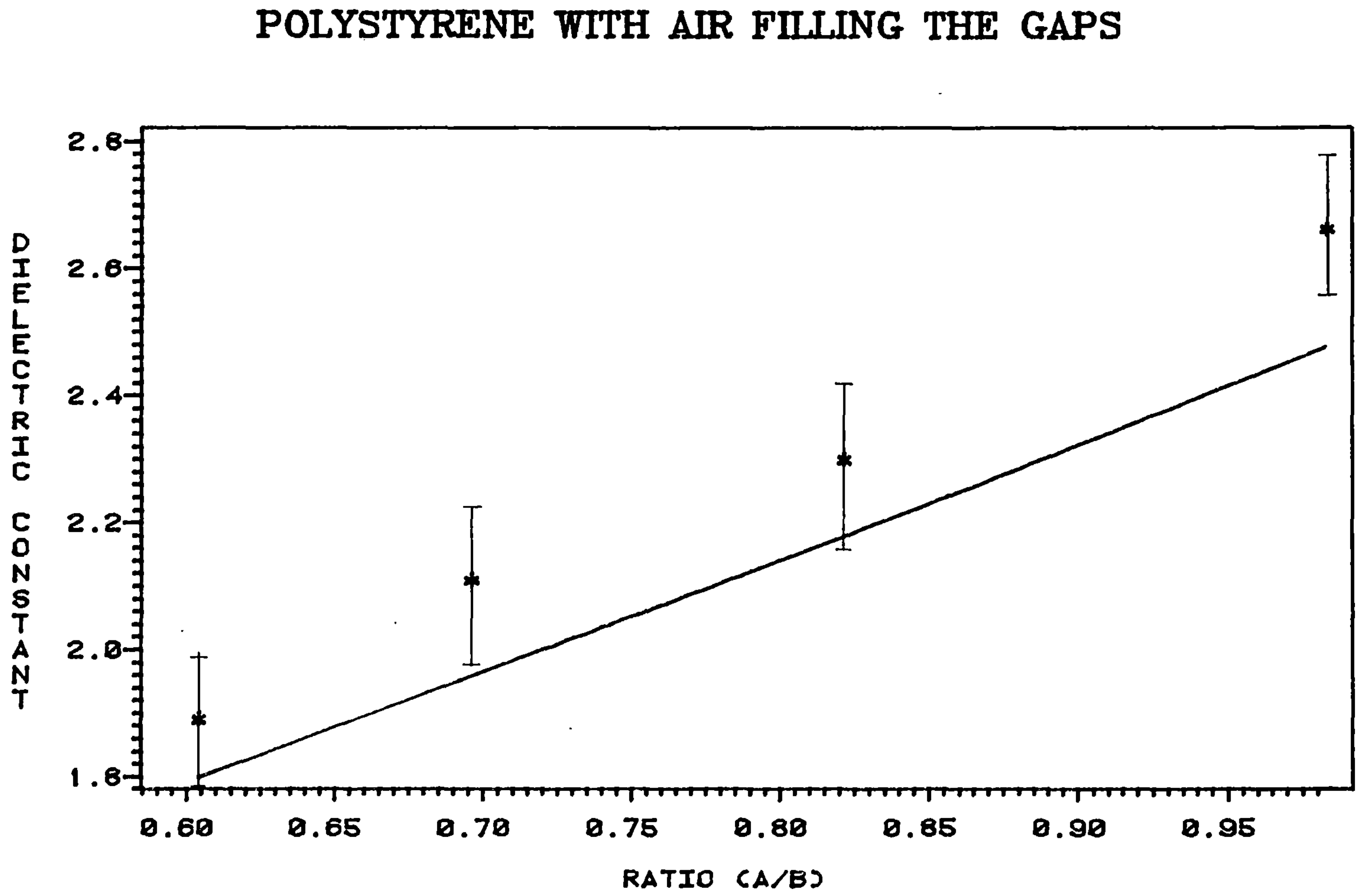


Figure 40. The solid line is determined from Eq. 5.15. Polystyrene has a dielectric constant of 2.55.

air and water, other fluids such as acetone and methanol, are used to fill the gap. The dielectric constant is plotted as a function of the gap fluids for a cylinder with a dielectric constant of 20, as shown in Figure 43. The agreement between the measurements (dots) and the calculated values (solid line) is very good indicating the applicability of the correction equation over a wide range of gap-fluids.

The previous measurements were made on dielectrics of one piece filling the coaxial transmisson line. In contrast to this, rock samples are segmented into small pieces because they are not long enough to fill the coaxial line in one piece. The correction equation was used to check the dependence of the dielectric constant on the segmentation of the core. A solid cylinder of dielectric constant 10 was initially constructed of one piece and its dielectric constant was measured. The cylinder was then cut into four pieces and dielectric constant was recorded. Finally, it was cut into nine pieces which were fit into the entire length of the coaxial line. The measurements on the segmented cylinders were done with both air and water filling the gaps. The results are presented in Table IX where the measured values were in good agreement with those calculated from the correction equation. This indicates that carefully segmented rock core materials should lead to the same results a one solid core sample.

Application of the Correction Equation to Sandstone Cores

Since the correction equation proves to be satisfactory in extracting the dielectric constant of the core from the measured dielectric constant of the coaxial line (ε), it can be directly applied to determine the dielectric constant of the core as follows

$$\varepsilon_c = \frac{\ln({}^{c}/b)}{{}^{1}/\varepsilon_m \ln({}^{d}/a) - {}^{1}/\varepsilon_{fg} \ln({}^{db}/ca)} \tag{5.16}$$

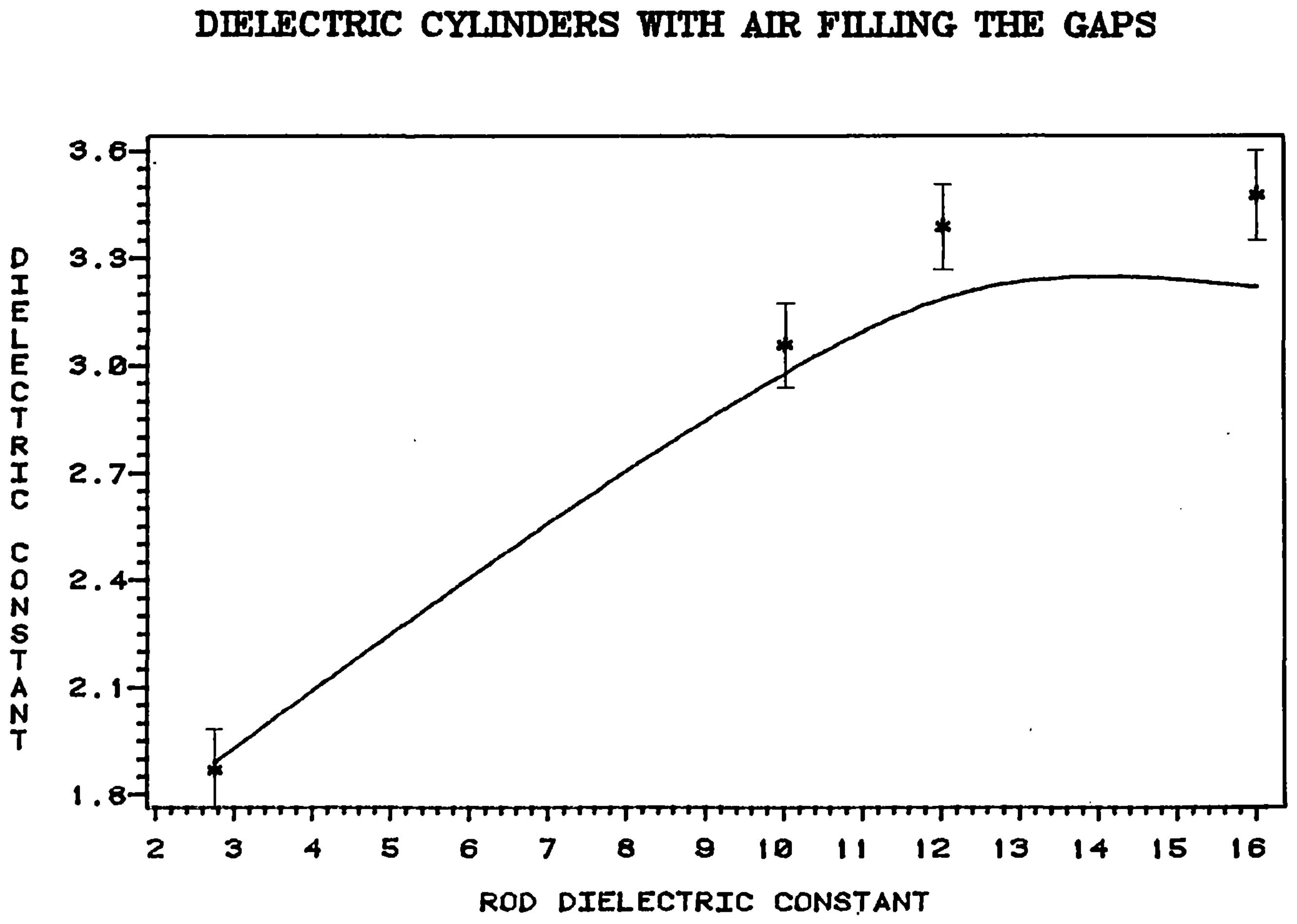


Figure 41. A fixed ratio of (a/b) is used with air filling the gap.

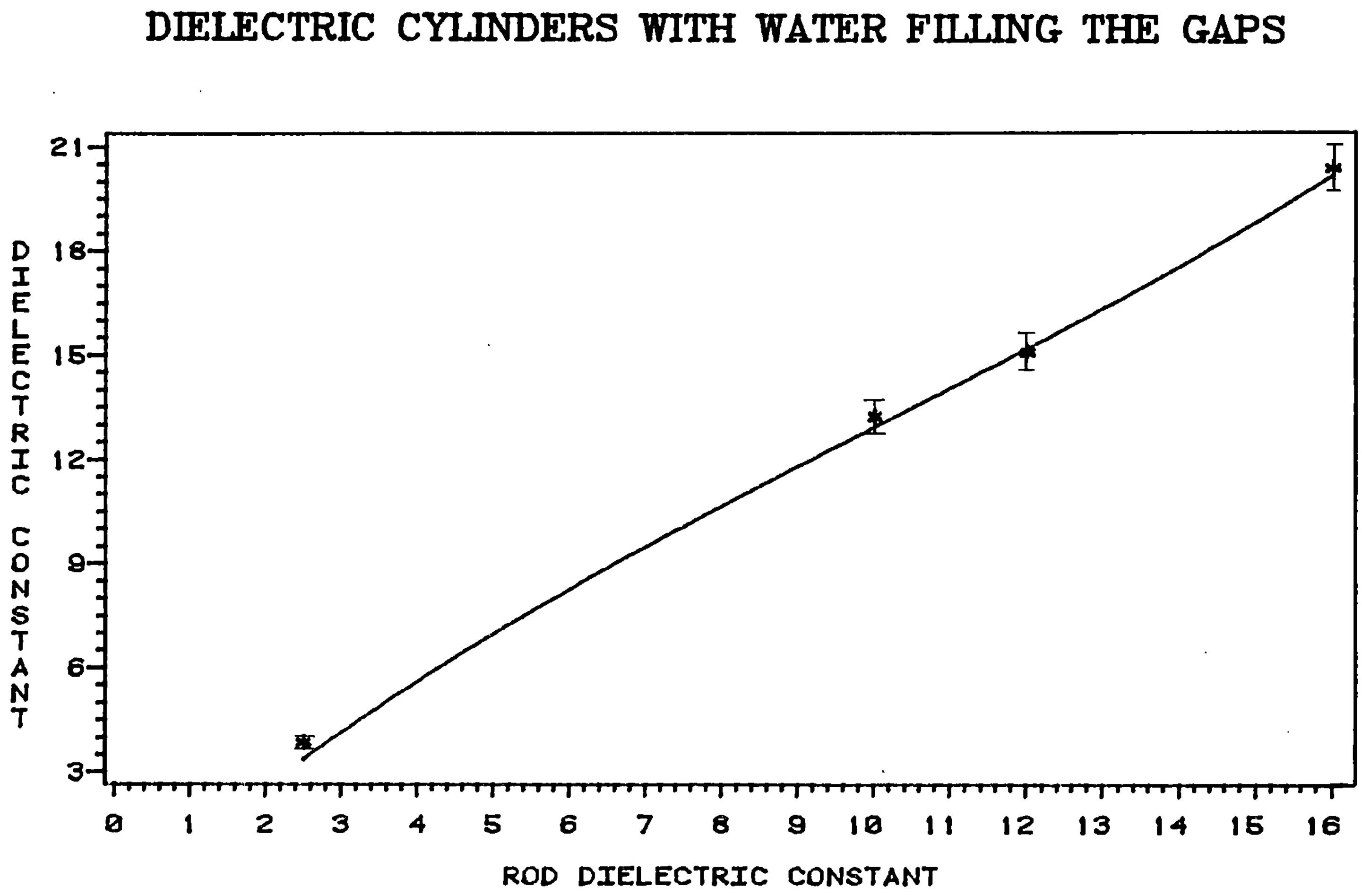


Figure 42. Water is used to fill the gap for the same measurements as in Figure 41.

TABLE IX

DIELECTRIC CONSTANT OF THE COAXIAL WAVEGUIDE CONTAINING CYLINDRICAL SOLID DIELECTRICS AS A FUNCTION OF NUMBER OF PIECES. DIELECTRIC CONSTANT OF THE CYLINDER IS 10.

	Air Filling the Gap		Water Filling the Gap	
# of Pieces	Measured	Calculated	Measured	Calculated
1	2.73	2.74	13.81	13.45
4	2.53	2.74	14.03	13.45
9	2.61	2.74	13.31	13.45

TABLE X

COMPARISON BETWEEN MEASURED (ε) AND CALCULATED VALUES (ε_c) OF THREE DIFFERENT MIXING LAWS FOR THREE SAMPLES OF SANDSTONE CORES.

	Air Filling the Gaps				Water Filling the Gaps			
	ε_c			ε_m'	ε_c''			ε_m''
Sample	SRE	EMT	TOE		SRE	EMT	TOE	
1	3.19	3.22	3.34	3.40	20.72	22.03	25.47	23.83
II	3.53	3.56	3.79	3.63	8.94	9.11	10.95	10.39
III	3.97	4.02	4.43	3.54	17.44	18.57	22.04	21.75

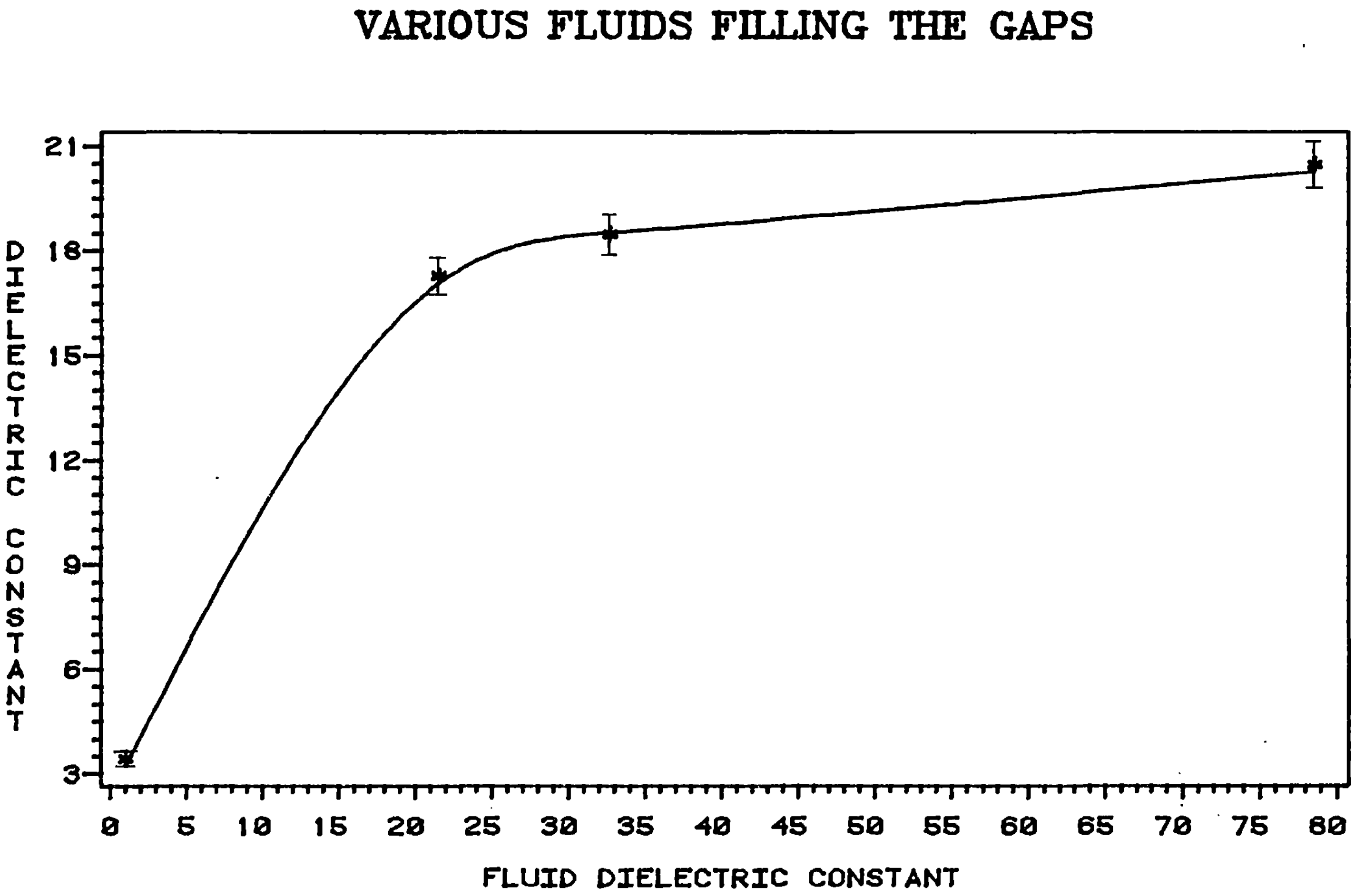


Figure 43. The dielectric used has a dielectric constant of 20 and the solid line is determined from Eq. 5.15.

where ε_m is the measured dielectric constant of the coaxial waveguide and ε_c is the composite dielectric constant of the core material. Measurements on sandstone cores, which were cut into cylinders to fit the coaxial transmission line, are discussed in the following section. The porosity is determined independently using a water saturation technique in partial vacuum. The dimensions of the inner radii are designed so that the ratio (a/b) would not be very close to unity, as outlined previously. Fully and partially saturated cores are investigated, with either water or air surrounding the specimen. The procedure previously used to obtain a value of the dielectric constant of a dielectric rod was adopted for a coaxial sample holder. This procedure allows the determination of the rock properties independent of the geometry of the waveguide and sample. Application of this procedure focusses attention on the material properties of the rock core in order to evaluate a mixing law which can be used to describe consolidated materials. The assumption made in establishing this mxing law is that all information concerning the physical properties is included in the magnitude of its dielectric constant, rather than the mathematical form of the mixing law. The preliminary step of the measurements involves the determination of the solid dielectric constant for the cores. This procedure involves 1) determining the core dielectric constant for air saturated samples using Equation 5.16 and 2) applying the EMT formula to determine ε_s (as discussed in the first section of this chapter). This procedure provides the parameters needed to determine the composite dielectrtic constant, namely, ε_s, ϕ and ε_f and ε_{fg}.

Fully Saturated Cores. Three different sandstone cores, which have various porosities and dielectricconstants, are used in this investigation. The dielectric constant of the cores are calculated (from the knowledge of ε_s, ϕ and ε_f) using different mixing laws. These calculated values are substituted in the correction equation (Equation 5.15) to determine the dielectric constant of the waveguide which are then compared with the measured dielectric constant of the coaxial line. A comparison of the measured results to the calcualted values from TPO, EMT and TQE, for both water and air filling the gaps, is presented in Table X. The results show that TQE is more accurate when the sandstone cores are fully water saturated. This indicates that the inversion of the correction equation (Equation 5.16) is reliable in determining the core dielectric constant from one measurement of the coaxial line.

Partially Saturated Cores. When the core samples are partially saturated with water, similar procedures are used to evaluate the measurements as those followed for fully saturated. Two of the previous three samples are used. For those measurements only air could be used to surround the specimen, so that the exact amount of water which is saturating the porous cores could be determined.

The procedure begins by fully saturating the sample, then placing it in a coaxial line while the weight of the system is recorded. This system is heated to 110 - 120°C to allow some of the water to evaporate uniformly from the core. After the system cools down, it is weighed and the difference in the weight determines the amount of air replacing the water. The partial saturation of water (S_w) is determined using this procedure.

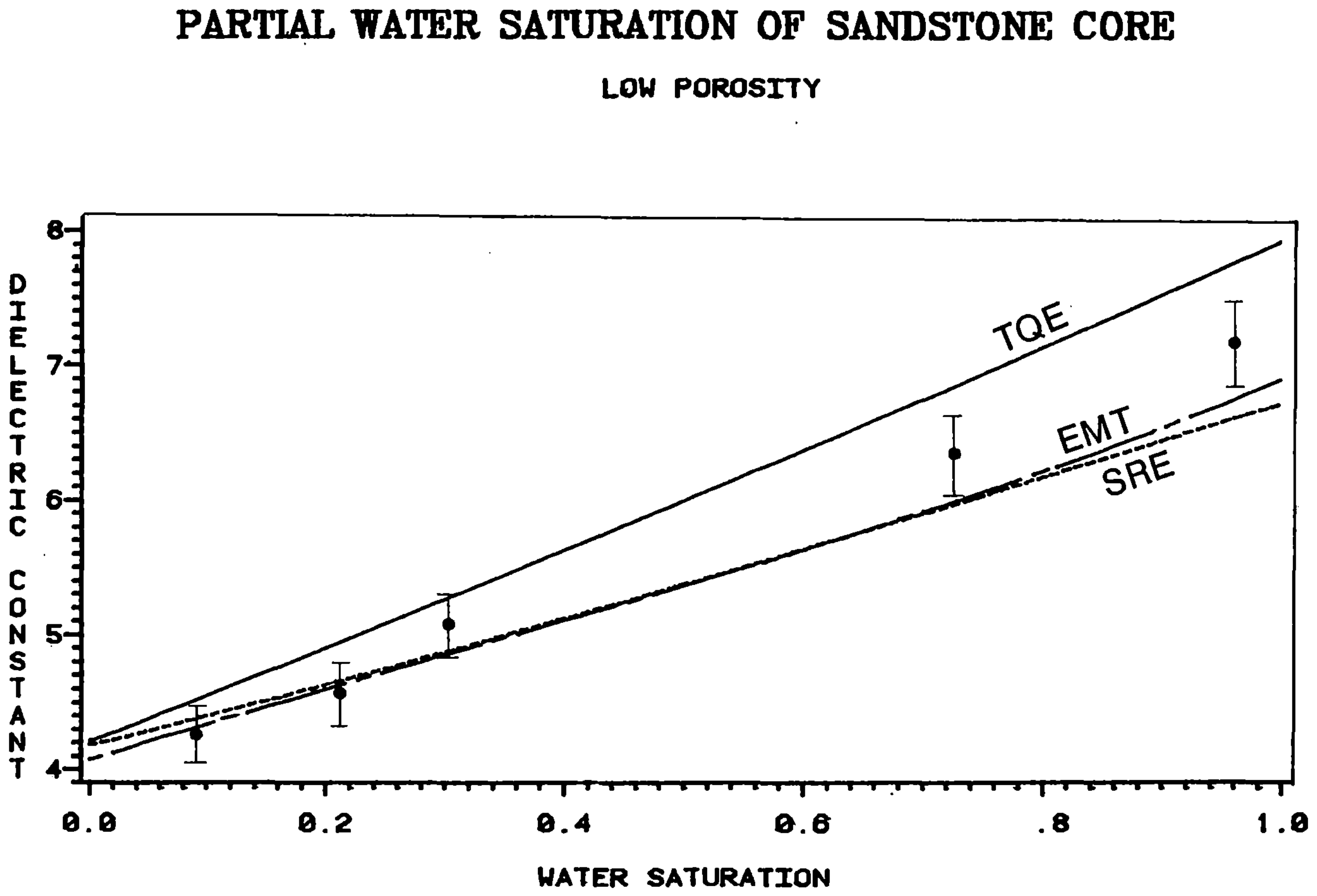
The dielectric constant of the coaxial line is measured and the core dielectric constant is calculated using Equation 5.16. This value is compared with the calculated value of the partially saturated system using EMT and SRE. The results are plotted for the dielectic constant of the core as a function of water satuaration . For the first sample, as seen in Figure 44, SRE and EMT present similar behavior. The sample has a very low porosity (7%) which explains why the dielectric constant is relatively low even when fully water saturated it does not vary much from $S_w = 0$ to $Sw = .80$. On the other hand, if the porosity of the sample is higher (30%) as seen in Figure 45, the composite dielectric constant is higher than the first case and the change in ε as a function of S_w is more obvious. Since EMT and SRE display similar curves, only SRE is presented in Figure 45.

The close agreement of the SRE with the measured results offers the potential for applying dielectric techniques to measure the water saturation. Using the inverted form of the SRE, the water content is calculated from measurement of the composite dielectric constant.

Flow of Fluids Through Porous Media

The physics of fluid transport through porous media has become a basic consideration in many applied fields such as soil mechanics, groundwater hydrology, petroleum engineering, water purification, industrial filtration and others. The subject is important in studying pollution caused from accidental spills and industrial leakage of immiscible fluids, and the transport of fluids in oil reservoirs. The problem is complicated by the fact that many of the fluids used in industrial processing are water-immiscible and highly resistant to biological degradation. Once introduced into the system they become long-term polluting sources. This is particularly true of immiscible fluids whose low solubility in water means that their transport is not affected appreciably during rain infiltration through the medium. The slow leaching of immiscible fluids such as carbontetrachloride and crude oil results in the existence of these pollutants for long periods of time lasting in some cases for decades with a continuous serious threat to local aquifers (Dunlap and Shew, 1981). The practical examples in oil reservoir engineering include cases of water flooding, in which water is injected into the oil region. In groundwater hydrology the common examples are cases involving water flow into coastal aquifers (Gupta and Greenkorn, 1974).

The current section is concerned with the application of dielectric techniques to the study of multiple flow of fluid through porous materials. The experiment is directed to providing a practical means of studying the flow properties in the laboratory, rather than contributing new results in the subject. The main purpose is to determine if dielectric measurements can be used to measure the partial saturation (for water and other fluids) in the presence of more than one fluid. Another aspect of the flow characteristics studied is



PARTIAL WATER SATURATION OF SANDSTONE CORE

LOW POROSITY

Figure 44. The low porosity (Φ = .07) of the sample explains the relatively small values of the dielectric constant.

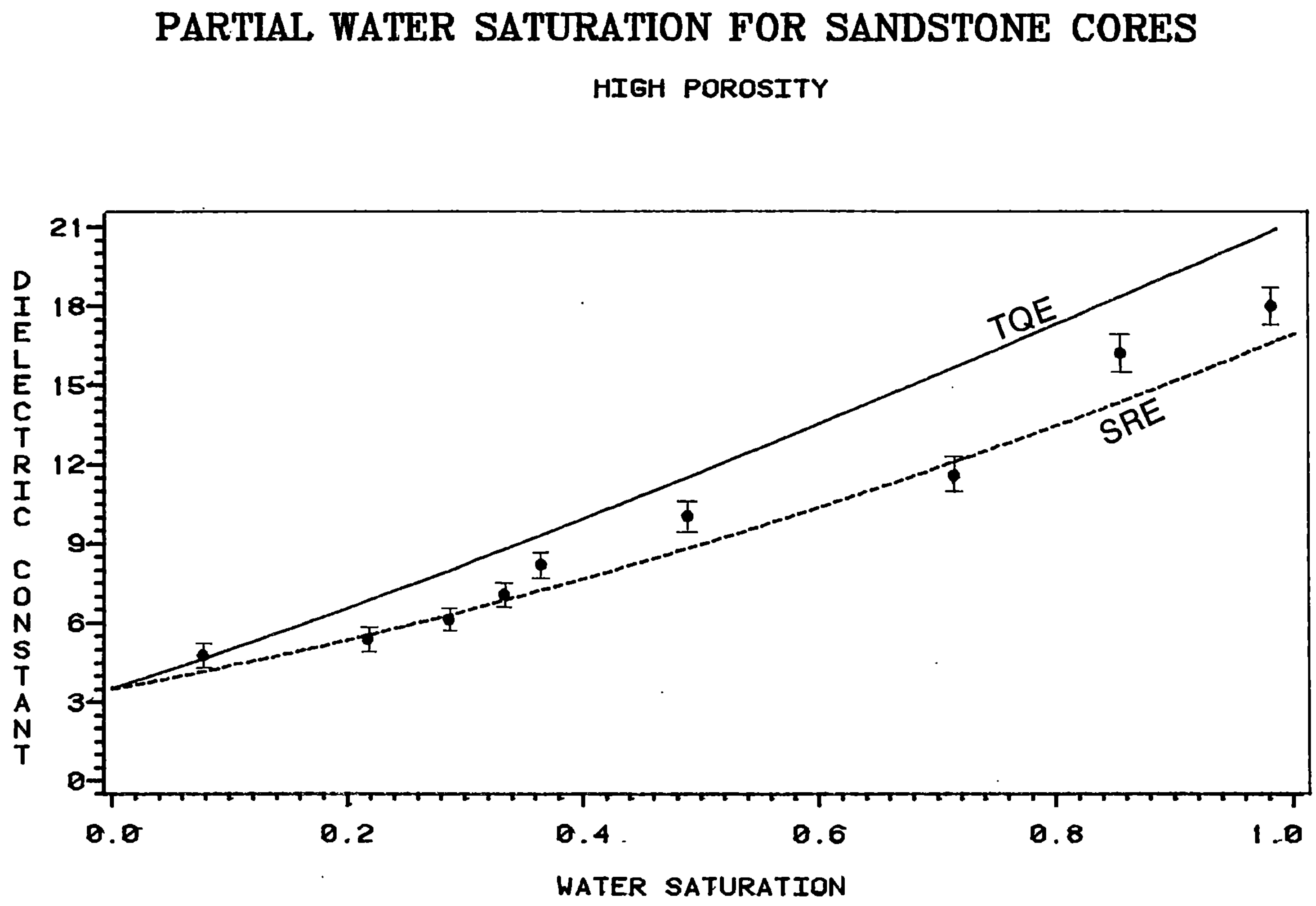


Figure 45. Same as in Figure 44 for a core which has a higher porosity ($\Phi = .30$). EMT curve was excluded.

the dependence of the retained fluids on the wetness history of the solid particles. The water-immiscible fluids of interest are mainly carbontetrachloride and crude oil. Two additional fluids are introduced in the flow procedure to alter the flow characteristics. Those include water-solvent (methanol) and an oil-solvent (cyclohexane). Surfactants in water solutions are used as a means of increasing the recoverable fluids. Ottawa sand is used as the porous media through which fluids flow. The first set of the experiments deal with carbontetrachloride and water interchanged in saturating and flushing a porous system. This is compared to other measurements in which differences in flow properties and retention capacity between carbontetrachloride and hydrocarbons are determined in the presence of water.

Replacement of fluids

When two immiscible fluids are present in a porous medium, parameters such as wettability and capillary pressure should be taken into consideration. The wettability depends on the adhesion tension between the solid surface and the coating fluid (Melrose and Brander, 1974). When oil and water are present in a system, the material could be water-wet, neutrally-wet or oil-wet. One of the fluids is called the wetting fluid while the other is the nonwetting fluid. These parameters have been studied using the dielectric technique. If the material is homogenous, as is the case for ottawa sand, and the viscosity of the displacing fluid is equal or greater than that of the resident fluid, the mixing zone between the two fluids is fairly short and has been well described in the literature (Perkins and Johnson, 1963).

When ottawa sand is fully saturated with water (Figure 46) the composite dielectric constant is relatively high due to the high dielectric constant of water. When carbontetrachloride ($\varepsilon_f = 2.238$) is introduced (System I), the net composite dielectric constant gradually decreases with time until it reaches a minimum value at $\varepsilon_m = 4.57$ (Phase A, Figure 46). Further carbontetrachloride flow does not lead to a change in this value. The constant magnitude of ε_m during the flow of carbontetrachloride is reproducibly higher than the value obtained when the medium is completely saturated with carbontetrachloride. Since water and carbontetrachloride have similar viscosities (.969 cp for carbontetrachloride and 1.002 cp for water, at 20°C) the displacement of water by carbontetrachloride is both efficient and fast. This could be explained by the observation that ottawa sand is neutrally wet in the presence of carbontetrachloride and water. Water displacement is called the drainage of water (see Figure 13). It is clear that a constant partial saturation of water (S_w) was reached very fast (after 0.5 minutes) after which no water can be displaced. This fact is represented by the constant ε_m (from 0.5 minute to 3.8 minutes). However, the amount of water (connate water) trapped in the medium (Phase A, Figure 46) can be determined quantitatively from the dielectric measurements using the flowing equation

$$S_f = \frac{\varepsilon_{ws}^{.75} - \varepsilon^{.75}}{\varepsilon_{ws}^{.75} - \varepsilon_{fs}^{.75}} \qquad (5.17)$$

where ε_{ws} and ε_{fs} are the dielectric constant of the medium saturated with water and fluid, respectively and ε_m is the measured dielectric constant of the system at the time of investigation. Derivation of Equation 5.17 is outlined in Appendix B. The three measurements (ε_{ws}, ε_{fs} and ε_m) are used in the equation to obtain the fluid saturation(S_f) without a need for reference values of the dielectric constant and the measurement of porosity. Application of this technique to more complex flow sequences involving both miscible and immiscible fluids is the major advantage of the dielectric measuring technique over other direct methods.

Since the porous medium (ottawa sand) is said to be a neutrally wet (System I), the introduction of water into the system leads to a sharp increase in the dielectric constant which soon levels off at a value less than that of the fully water saturated (Phase B, Figure 46). This difference is due to the trace amount of carbontetrachloride retained in the system. This process is called the imbibtion (Figure 13) where the system is resaturated with water. The failure of the asymptotic curve to reach full saturation value is reflected by the dashed line in the imbibition process. The amount of carbontetrachloride was determined from Equation 5.5 and found to be 12%.

The interaction between solid particles and different (saturating/flushing) fluids can be studied using dielectric techniques. Such properties can be achieved by reversing the fluid sequence. The solid/liquid interaction is an important factor, particularly in the oil recovery enhancement (Raimondi and Torceso, 1964). When the sequence of the saturating/flushing fluids is reversed (System II), the capacity of the ottawa sand to retain fluids changed (Figure 47). The Figure shows the alterations in the dielectric constant of ottawa sand initially saturated with carbontetrachloride following the introduction of water (Phase A, Figure 47). The rapid increase in the dielectric constant in the early stages of Phase A reflects the displacement of carbontetrachloride by the displacing fluid (water). The asymptotic value reached in the later stage of Phase A is in contrast to the corresponding value in the later stage of Phase B of System I (Figure 46) in that it is closer to the dielectric constant value of the water saturated system. The variation in the difference in both systems could be mainly due to differences in the affinity (wettability) of the saturating fluid to the solid component. The relatively small difference between the asymptotic values of ε_m and that of the fully water saturated condition might be accounted for by the affinity of ottawa sand to water. However the inability of water in System I to remove at least the same amount of carbontetrachloride as did the first water wash in System II makes this suggestion questionable and therefore, the ottawa sand is said to be neutrally wet in the presence of these two fluids. The displacement procedure is extended by introducing methanol as a miscible component (ε_f - 32.63) into the flow history. Flushing with methanol (Phase B, Figure 47) reduces the dielectric constant as methanol replaces water. The asymptotic value ($\varepsilon = 11.5$) reached in the later stage of the methanol wash is half the corresponding value ($\varepsilon = 23$) of the water saturated conditions. Because

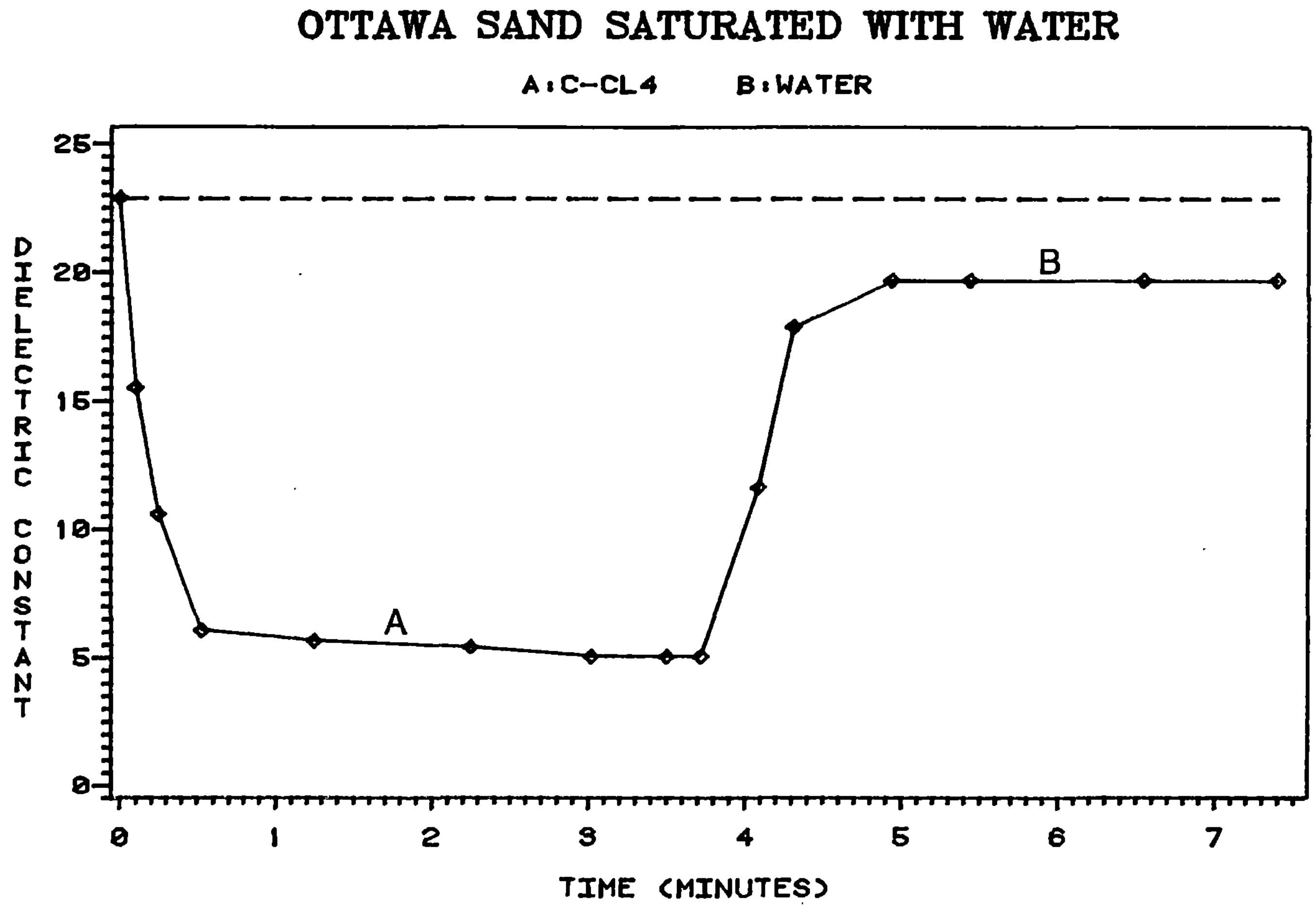


Figure 46. Sand was initially saturated with water then subjected to flow of C-CL4 (A) then water displacement (B).

the three liquids are colorless, it is not possible to visually observe the amount of previously retained carbon tetrachloride that had been removed. After a subsequent water displacement, the dielectrtic constant rises sharply and soon reaches a constant level at ε_m = 22. The inclusion of the methanol step in System II does improve, though slightly, the removal of carbontetrachloride from the porous material as evidenced by the relatively higher asymptotic dielectric constant ($\varepsilon_m = 22$) of the second water flushing as compared to that ($\varepsilon_m = 21$) of the first water wash. Since, in a separate experiment, water has completely removed methanol, the immiscible fluid left over in the medium is likely to be only carbontetrachloride, the amount of which is found to be 4% of the original volume introduced into the system. The fact that methanol has both a hydrophilic (-OH) and a hydrophobic (CH_3-) group gives it the characteristic to mediate the process of removing the carbontetrachloride during the second water wash. Unexpectedly, System II for a three treatment procedure (Figure 47) took less time to be completed than System I which included only two treatments (Figure 46). The reason for this lies in the observation that the first water displacement in System II ends in shorter time than the first carbontetrachloride wash in System I. Also, the methanol displacement in system II reduces the time needed for the second water flush and the two treatments together require shorter time (3.3 minutes) than the time (3.7 minutes) required for the second water treatment in System I. Again, as explained before, the mediating role of methanol in System II is easily envisaged because of the combined hydrophilic and hydrophobic properties of methanol.

The sequence used to study the crude oil flow through the porous medium was intended to be identical to that of carbontetrachloride to observe any difference in the flow of those fluids. The measurements were then extended to include the water and oil miscible fluids to improve the flow rate and reduce the retained fluids. When oil is present in a system and allowed to flow, it is generally broken into three fractions (Coats and Smith, 1964): flowing, dendritic and isolated. The flowing component is the fluid in the

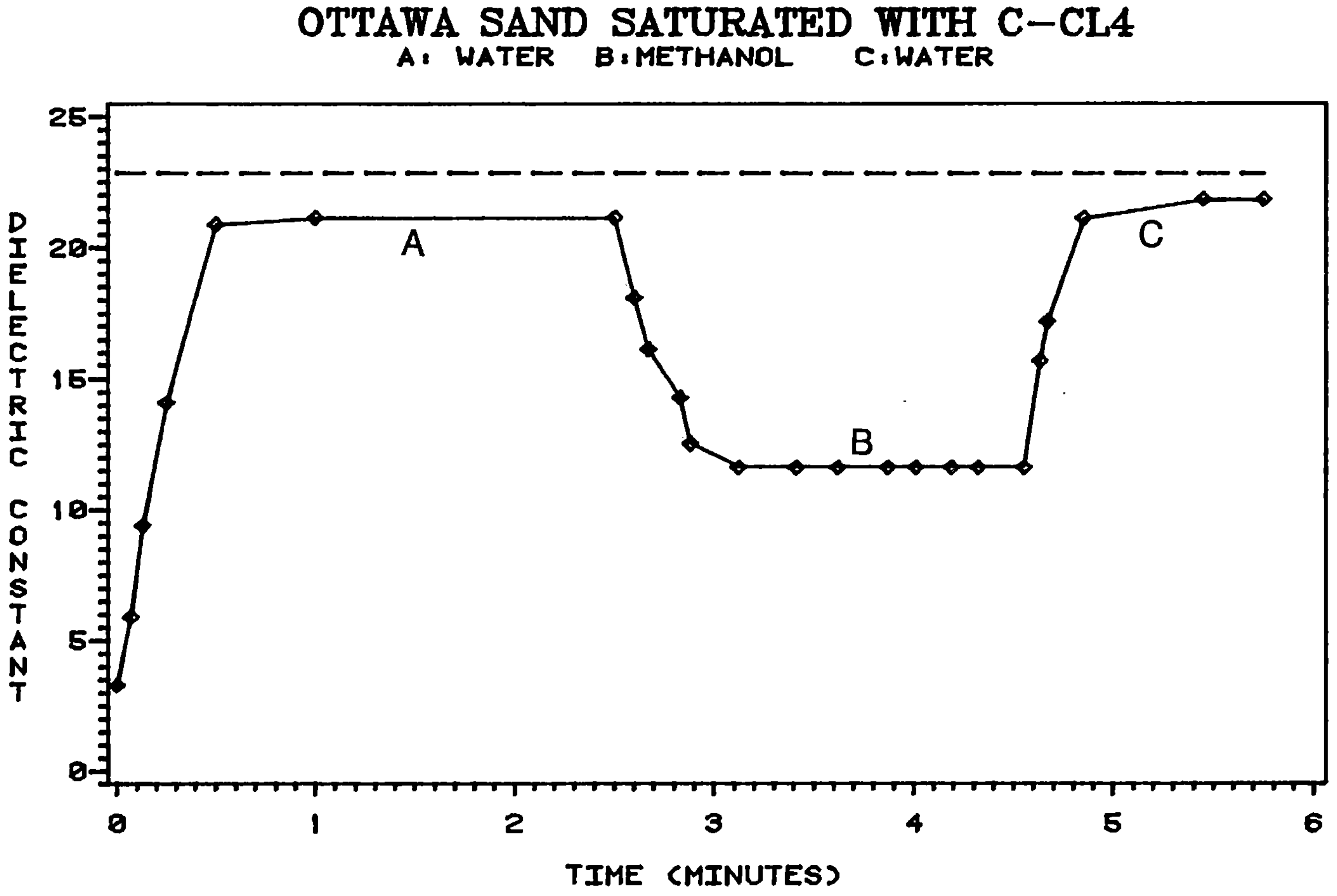


Figure 47. C-CL4 displacement (A) for initially water saturated sand, followed by methanol (B) and water (C) displacements.

pores which a phase flows in at least one throat and out at least one. The dendritic fraction of a phase is connected to the flowing fraction of that phase but does not exhibit flow by itself. The isolated fraction is completely surrounded by other phase through which no diffusion can occur. This amount is, therefore, not recoverable. The recoverable fraction is the sum of flowing and dendritic fractions. The sequence of flow was repeated with crude oil (System III and IV) instead of carbontetrachloride. In the water saturated system (Figure 48), the rate of replacement of water by crude oil is slower (2 minutes) than that (0.5 minutes) by carbontetrachloride due to its larger viscosity. The delay in the flow is due to the capillary pressure created by the presence of two immiscible fluids having two different viscosities, and no displacement can occur until the capillary entrance pressure is overcome (Jone, 1985).

In addition, the time taken (3.7 minutes) by 100 ml of carbontetrachloride to complete flush the system is 5 times faster than that (18.0 minutes) required by the same volume of crude oil. Once water is reintroduced (Phase B, Figure 48) the dielectric constant starts to increase until it levels off at a dielectric constant value of 16, but still not reaching the original value of the full water saturation ($\varepsilon = 23$). Interestingly, this difference ($\Delta\varepsilon$) is reproducibly greater ($\Delta\varepsilon = 7.0$) with crude oil (Figure 50) than with carbon- tetrachloride ($\Delta\varepsilon = 3$, Figure 46). The difference between the two situations may be accounted for if one assumes that a larger amount of crude oil as compared to carbontetrachloride was irreversibly adhered to the particles of the stationary solid component of the system following the water wash (Phase B in both Figures 46 and 48).

When the sand is fully saturated with crude oil, then flushed by water (system IV), a similar behavior is observed (Phase A, Figure 49). In the crude oil saturated system the difference between the asymptotic value of the dielectric constant and the value of fully water saturated systems is always greater ($\Delta\varepsilon = 9$) than the coresponding difference ($\Delta\varepsilon = 2$) when carbon tetrachloride is saturating the system. This difference along with the calculation made using Equation 5.17 indicates that more crude oil (36%) than carbontetrachloride (9%) is left in the system after the water flushing.

The behavior of the imbibition and the drainage in Systems III and IV leads to the belief that in the presence of water and oil, ottawa sand is more likely to be water wet. The amount of crude oil that has been trapped in Phase A (Figure 49) could be both dendritic and isolated, but for phase C, the only fraction left over is the isolated fraction. Water, in this case is called the wetting fluid while the oil is the nonwetting fluid.

When methanol is introduced, the dielectric constant sharply decreases (Phase B) indicating the replacement of water by methanol. Oddly enough, after the dielectric constant reaches its minimal value ($\varepsilon_m = 8$) it starts increasing gradually before levelling off at a value of 10. This phenomenon was not observed when the system was iniatially saturated with carbontetrachloride. One may speculate that during the early stage of Phase B methanol replaces water causing a sharp decrease in the dielectric constant until it reaches the value of 8. The subsequent gradual increase in the value of ε_m could probably be due to the replacement of crude oil by methanol. This successive action of methanol in removing water and crude oil can be attributed to the fact that methanol is more hydrophillic than hydrophobic. The reason why this phenomenon is not seen in the carbontetrachloride saturated system is due to the fast rate of replacement of water and carbontetrachloride by methanol which does not permit this phenomenon to be observed. Another factor could be that the amount of carbontetrachloride removed by methanol is minute so that the minimal situation is not observed. When water is reintroduced into the system (Phase C) a very sharp increase in the dielectric constant is always observed until a value of 17 is reached after which no change is noticed. This constant value ($\varepsilon_m = 16$) is higher than that ($\varepsilon_m = 14$) of Phase A suggesting that methanol is more efficient than water in replacing crude oil. These observations indicate that when a porous medium saturated with two immiscible fluids is subsequently flushed by a fluid which is miscible in one of them, the flow characteristic will be as follows. First, the flushing fluid will difuse in the miscible fluid

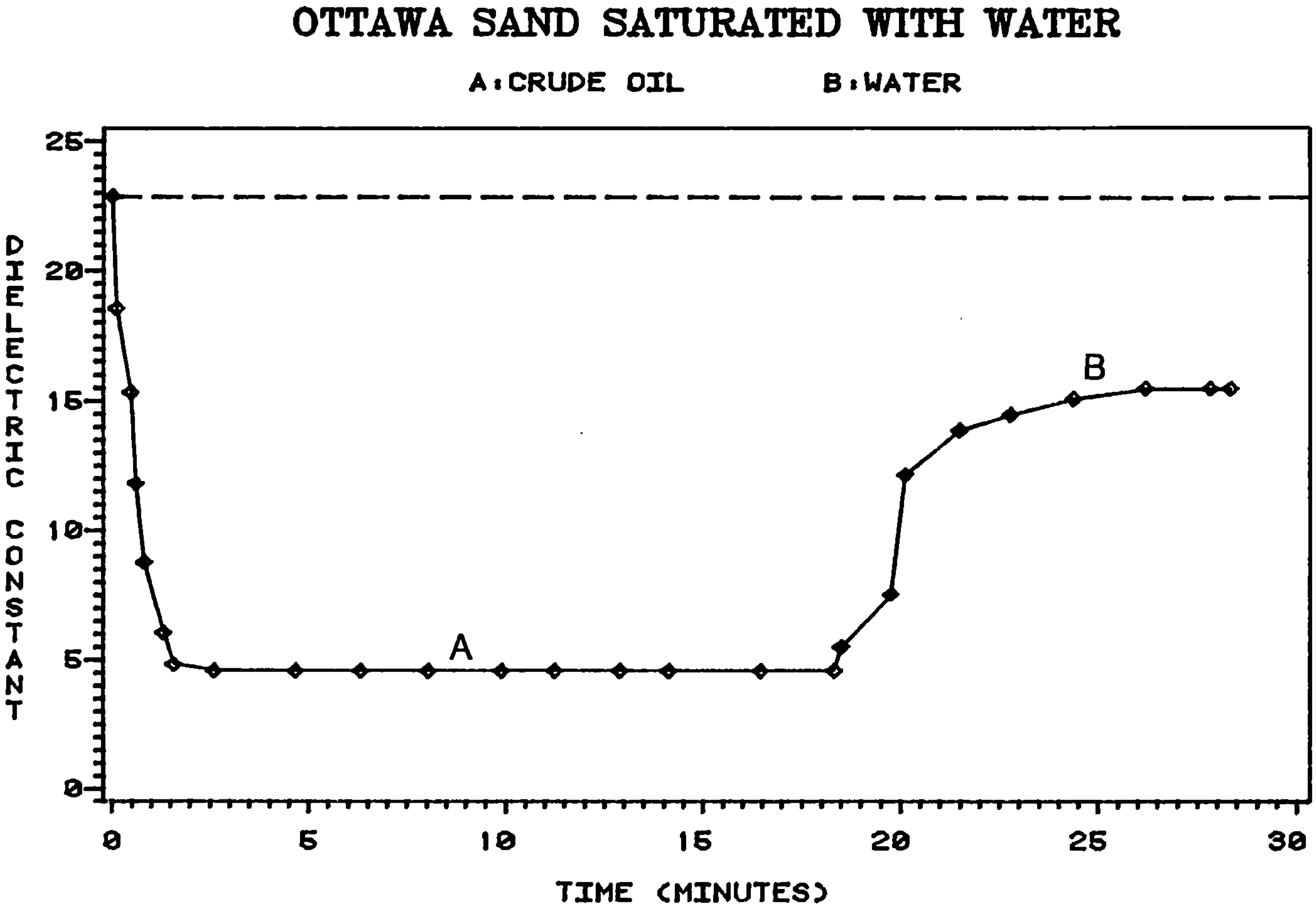


Figure 48. Water displacement of crude oil (B) is less effective than displacement of C-CL4.

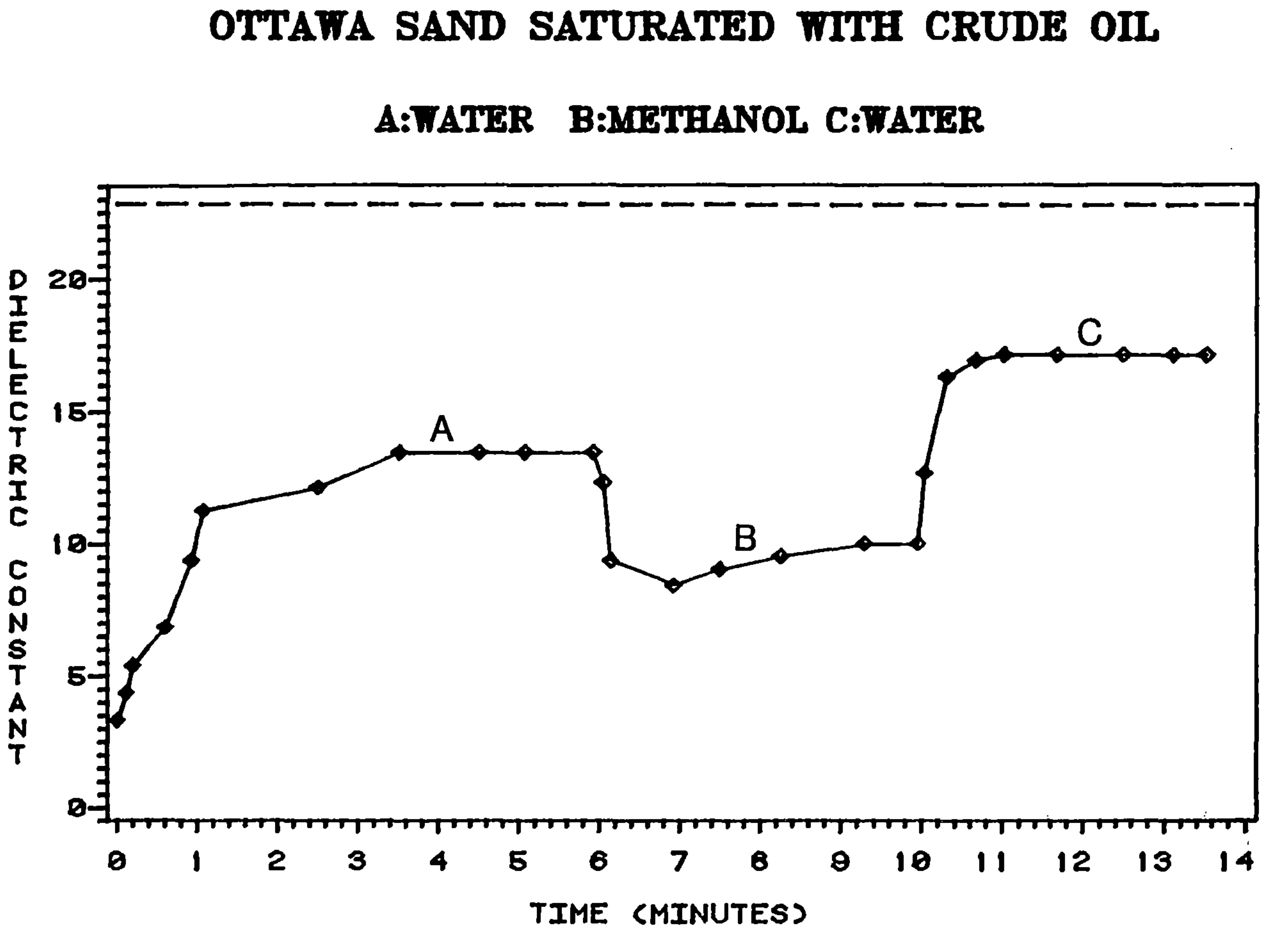


Figure 49. The introduction of methanol reduces the crude oil retention.

causing a fast removal of both fluids. The second step is taken when the flushing fluid starts to remove the immiscible fluid. Methanol is more efficient than water in replacing both hydrocarbons and chlorocarbons. This characteristic of methanol and the fact that it is totally removed by water offer an improved means of extracting crude oil and chlorocarbons in the presence of water because both are immiscible in water and in methanol. The amount of crude oil left over in the system after the initial water flush is 36% as compared to 21% left after the second water flush, as calculated from Equation 5.17. In addition, the time taken to complete the process of Systems III and IV (Figures 48 and 49) was reduced. It took a three treatment procedure (System IV) 50% of the time taken by a two treatment procedure (System III). This could be explained according to two effects. The first is due to the mediating effect of methanol, as discussed for Systems I and II (Figure 46 and 47). The second effect is the efficiency of water in replacing crude oil . Comparison of Phase A in the two figures shows that it takes 3 times as long (18.0 minutes) for crude oil to flush its volume through the water saturated system as (6 minutes) for water to flush the same volume through the crude oil saturated system.

The amount of retained immisciuble fluid (partial saturation) such as crude oil is further modified by the introduction of cyclohexane as an oil solvent having a dielectirc constant of 2.02. When the sand is initially saturated with crude oil (System V), the water displacement leaves 36% crude oil as shown in Phase A of Figure 50. A subsequent flushing with cyclohexane reduces the dielectric constant to a slightly higher value than that of the original because crude oil and cyclohexane have an identical dielectric constant (ε = 2.02). The discharge of the fluid during the late stage of Phase B is opaque indicating a considerable amount of crude oil remaining after the water flushing was removed by cyclohexane. This agrees with the conclusion (Thomas et. al, 1963) that miscible displacement is effecient in displacing nonwetting (oil in this case) fluid. At high wetting fluid saturation (phases A and C) some of the nonwetting phase is trapped in the pores and can not be flushed. Stalkup (1970) found that only part of the oil is flowable in the presence of high water saturation. The remainder resides in locations that are blocked by water, but can be recovered by molecular diffusion into the flowing displacement. However, large amounts of oil that initially seem to be trapped by water are eventually recovered by solvent (cyclohexane) injection. Raimondi and Torcaso (1964) found that some oil was trapped permenantly. This is the isolated fraction of the oil in the medium. The introduction of water into the system increases the composite dielectric constant (Phase C), but only slightly, above the original water displacement. The amount of crude oil and/or cyclohexane that is still occupying the pore volume is found to be 31%. But, since a considerable amount of crude oil is removed by the solvent treatment, the immiscible fluid remaining after the second water displacement must have been largely cyclohexane. When water is injected into a water-wet core containing water and hydrocarbon (as is the case in Phase C Figure 50), its entry into all pores is not delayed (Jones, 1985). This can be seen in the sharp increase of the dielectric constant in the early stage of Phase C. Being the wetting phase, water enters pores without having to overcome any capillary entrance pressure. Injected water (if it is the wetting phase) should displace all resident water. This is because the injected fluid is accesable to all pores. On the other hand, injected hydrocarbon can displace resident hydrocarbon only if it can enter all-water filled pores that contain isolated hydrocarbons. Thus, if oil is the nonwetting phase, injection of a solvent completely miscible with oil does not guarantee that all oil will be displaced. This is reason to believe that much (but not all) of the crude oil is removed by cyclohexane in Phase B. During the second water displacement (Phase C), water excludes cyclohexane as efficiently as it does the crude oil during phase A. It is clearly seen in Figure 50 that the cyclohexane treatment did not assist much in reducing the amount of the retained immiscible fluids. Thus, displacement with water immiscible fluids does not prove to be an efficient means of cleaning crude oil from porous media. However, the presence of methanol improves the displacement in spite of the fact that it is immiscible in crude oil. When methanol is introduced between the cyclohexane and the second water displacement (System VI), the

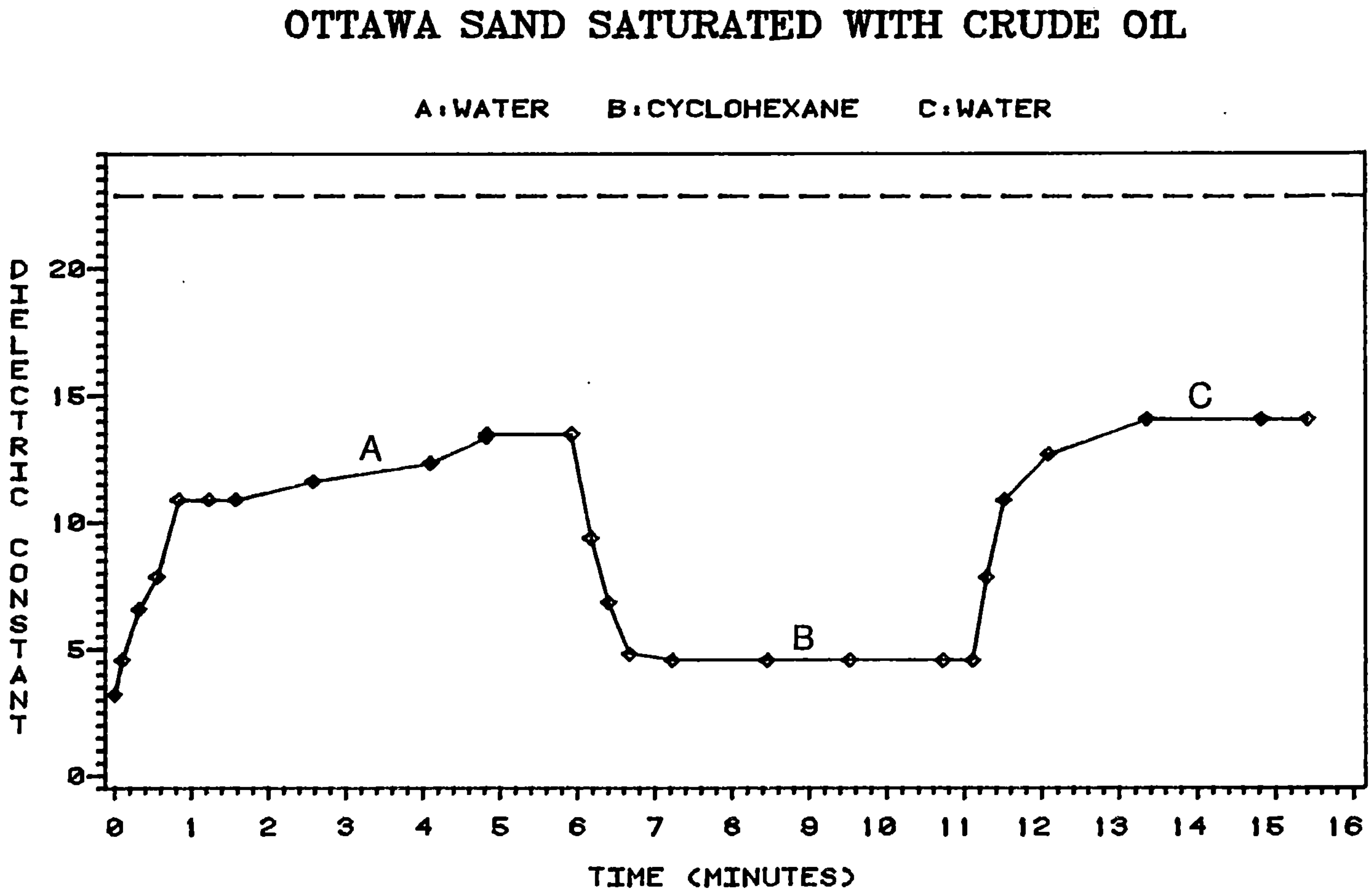


Figure 50. Inability of water displacement to remove cyclohexane.

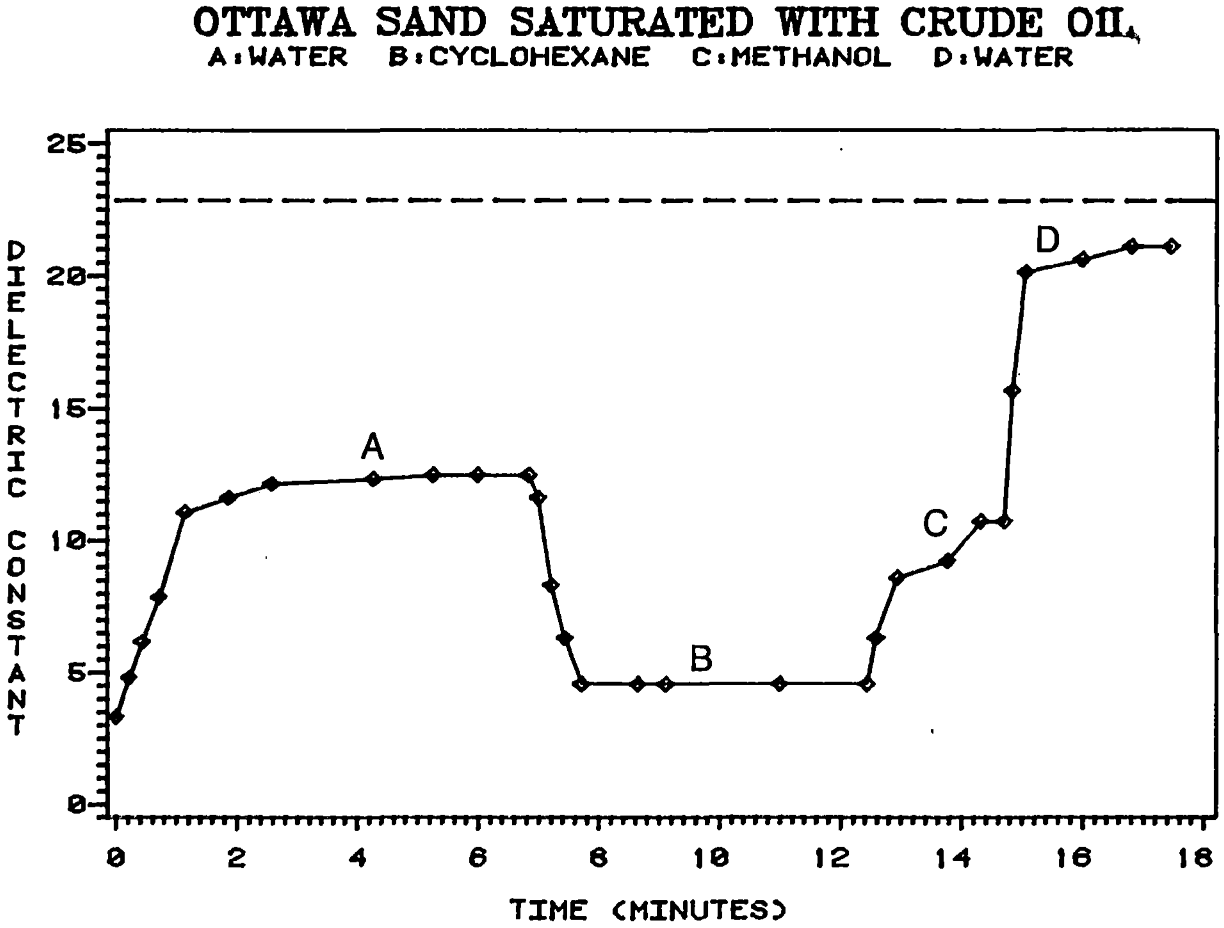


Figure 51. Combination of cyclohexane (B) and methanol (C) reduces the retained crude oil.

removal of the retained immiscible fluid (s) is considerably more effective than when each solvent is applied independently (Figure 51). Displacing with cyclohexane followed by methanol left only 10% immiscible fluid after the second water displacement. These observations along with the fact that methanol can be totally displaced by water provide a means for using these treatments. In general, in all enhanced recovery techniques, it is important to understand the nature of multiphase flow and the related parameters.

The flow treatments in oil reservoirs are often subjected to surfactant treatments as a means of increasing the petroleum supply (Fathi and Ramires, 1984). In two measurement sequences conducted using the dielectric measurement technique, it was found that the addition of a small amount of surfactant to water only slightly improved the ability of water to remove the crude oil in Systems VII and VIII as evidenced by the marginal increase in the composite dielectric constant (Figures 52 and 53). Moreover, no improvement in the effectiveness of cyclohexane to remove more crude oil by the addition of the surfactant was obtained and the overall composite dielectric constant was the same as when the final flooding was plain water. Although the surfactant initially removed slightly more crude oil, it did not alter the net retention of the cyclohexane-crude oil combination in the end of the process.

Finally, the ability of water to displace an immiscible fluid such as crude oil from the sand depends on the velocity of the interface flow. For ottawa sand, the percentage of the open pore space which was occupied by crude oil (retention factor) is shown in Figure 56 as a function of the pore velocity. The rate of decrease in partial saturation became less at higher flow velocities, indicating a residual partial saturation in the range of 30-33%. The retention of crude oil at even the highest velocity flow is still considerably greater than carbontetrachloride whose retention factor is typically 9%. If both these immiscible fluids were involved in separate accidental spills, a given volume of crude oil would be stored with a volume approximately five times larger than the medium retaining the same volume of carbontetrachloride. The retention or partial saturation of those immiscible fluids plays

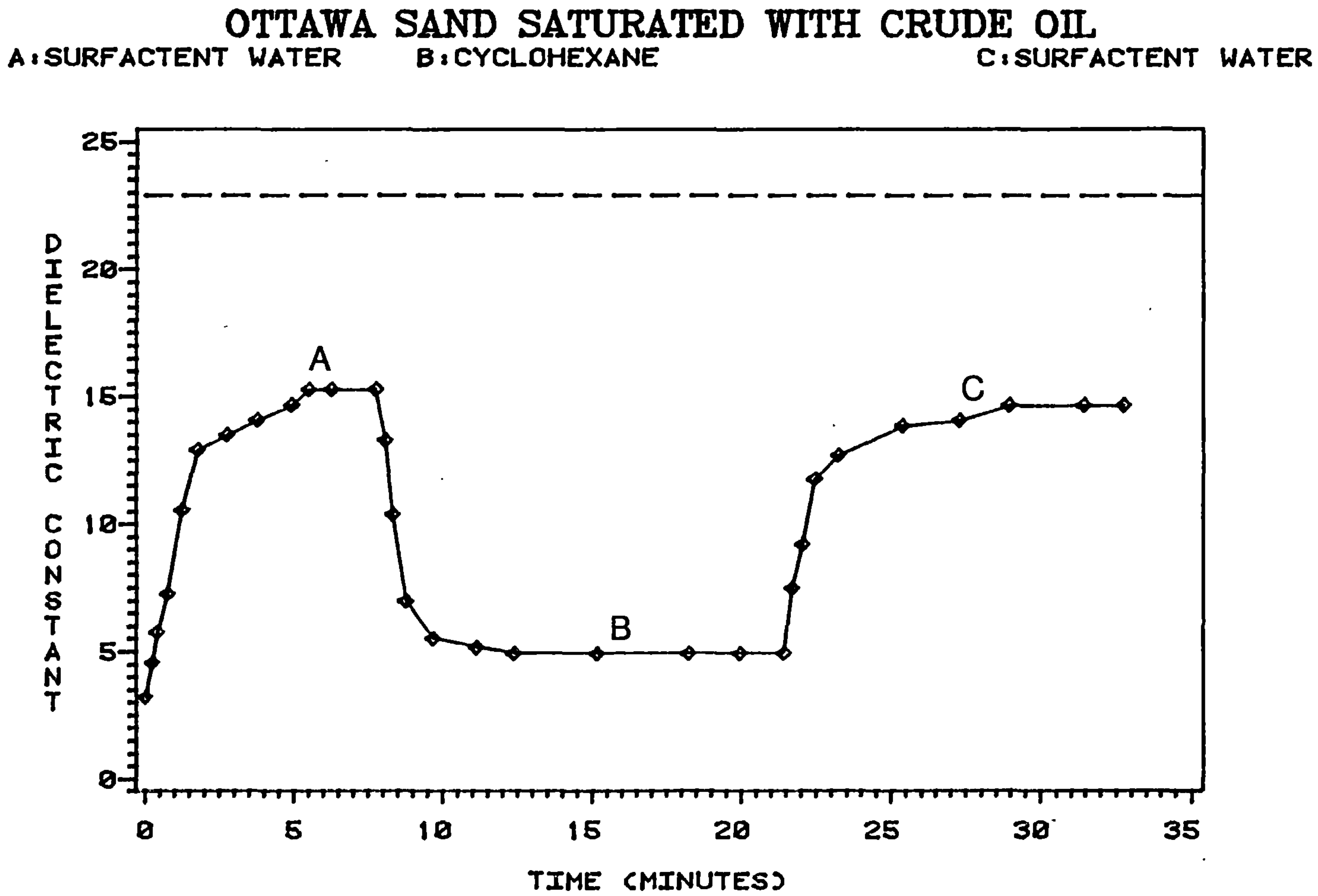


Figure 52. Surfactant Water Displacement

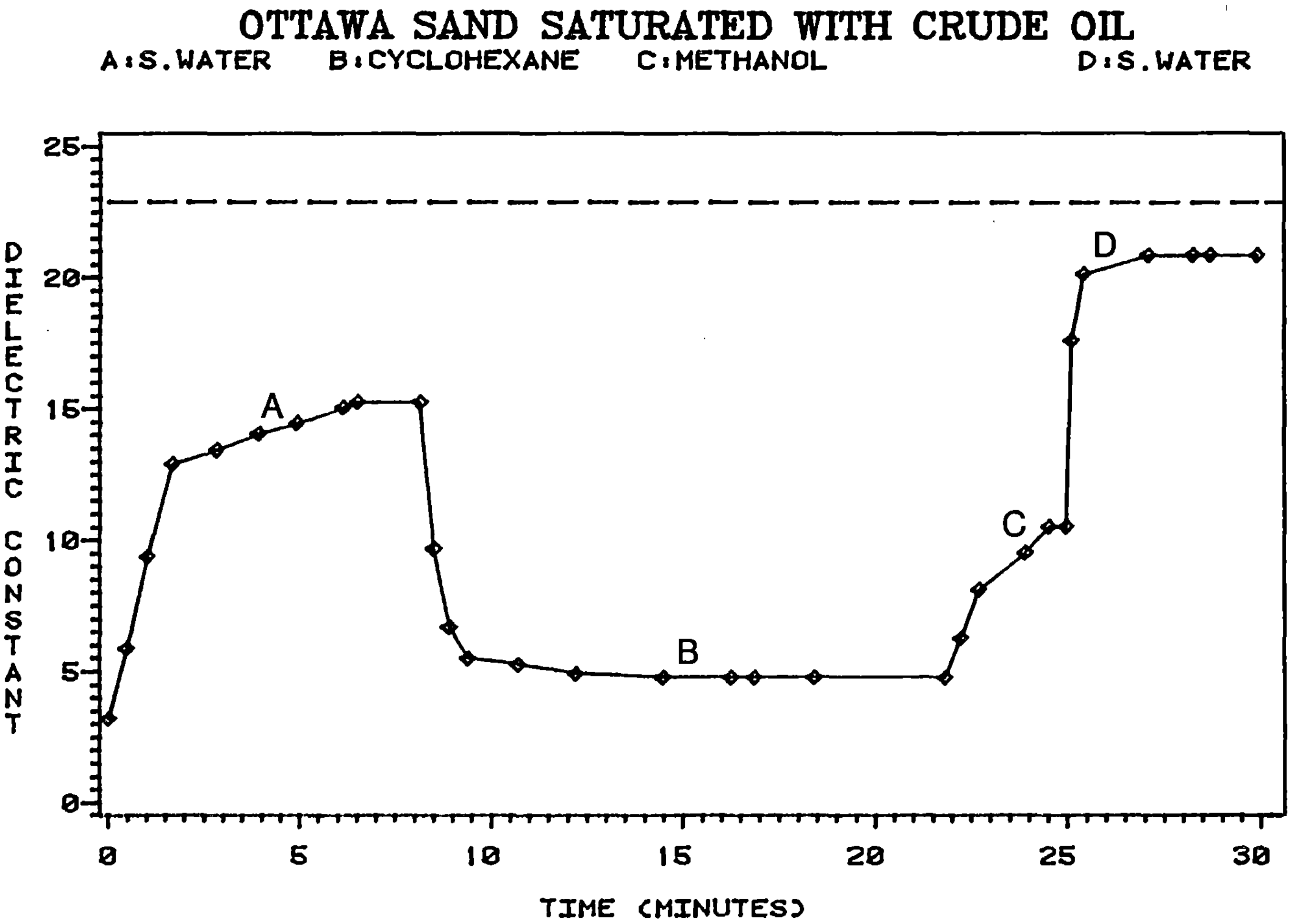


Figure 53. Same as in Figure 51 for surfactant water.

an important role in determining which long-term contaminated medium would be influenced by any remedial measures (Duffy et al., 1980).

CHAPTER VI

CONCLUSIONS

Microwave dielectric techniques can be applied to determine the properties of porous media and hetrogenous systems. The dielectric constant of a solid (ε_s), in a two component system saturated with air, can be determined from the measured dielectric constant of the system using the Effective Medium Theory (EMT) mixing law. The applicability of EMT to such a system (solid and air) is not surprising since the theory was originally derived for a two component system, and dry materials have a real dielectric constant independent of frequency. Since different shapes of the solid particles give similar results it is concluded that particle shape does not affect the measurement. It seems that as long as the particles have an average diameter smaller than the wavelength used, particles with irregular shapes behave in the system as if they were regular. For this, the depolarization factor (A) for spherical particles in the EMT (A=1/3) is employed for both regular and irregular particles. When unconsolidated porous media are saturated with a wide range of fluids, no mixing law suffices over the whole range of dielectric constant. This situation results because of the difference in permanent dipole moment of the saturating fluids. The EMT is the most accurate mixing law to be applied when the system is saturated with a fluid having a low dielectric constant ($\varepsilon_f<10$) In the case of high dielectric constant fluids ($\varepsilon_f>10$), particularly water, the appropriate mixing law to be used is the Three Quarter Equation (TQE). Such segregation in the application of the mixing laws is justified as follows. The applicability of EMT to two component systems with saturating fluids having low dielectric constant is due to the fact that such fliuds have either very low or negligible dipole moments and thus, their behavior in the system is very much like air. On the other hand, the picture is different for fluids with a high dielectric constants; particularly water, where the dipole moment is appreciable. In this situation, mixing laws (including EMT) would not work with water as they do with nonpolar fluids because such mixing laws do not take into account the effect of boundary layers of water adsorbed to the solid surface particles. Such water-solid surface interaction (Lange, 1983) affects the measured dielectric constant because the dielectric relaxation associated with water adsorped to the solid differ significantly from that of water in bulk. This difference in the behavior of water in the presence of porous media lead to the failure of EMT to describe the experimental findings in the fully saturated porous media. The adsorption of water to the solid surface form what is called double layer of water in the surface. Such adsorption lead to the prohibitation of water dipole to rotate, resulting in the decrease of water dielectric constant. It has been reported that the dielectric constant of such an oriented water layer is approximately 6. Following this argument, full water staturation measurement should result in values less than expected by EMT. But the contrary was observed indicating that water does change its behavior. This work has shown that the various mixing laws investigated are not critically dependent on the shape or surface roughness of the matrix when the system is fully saturated. If water saturation is not 100% (partial saturation) the system becomes more complex because of the mutual interaction between the three components (solid, air and water) which can significantly affect the static as well as the dynamic properties of the system. The failure of TQE to describe a partially saturated system is due to the fact that the dielectric constant of water structurely bound to a solid particle surface is much lower that that of free water (Bockris and Reddy, 1970). The first monolayer of water adsorbed to a surface has the lowest dielectric constant, the dielectric constant of successively adsorbed layers increases until it reaches that of free water. The successful application of EMT in such a system is because the solid matrix and the amount of water coating it behave as one component saturated with air. The fitting of

Square Root Equation (SRE) to partially saturated systems is empirical. However the two-step calculations and the cubic form of EMT makes it cumbersome to apply to multicomponent systems. The SRE, a simpler formula, is a mixing law of choice in such systems since it yields comparable results to the EMT. The SRE can be extended to include as many conponents in the system as required, a situation which is not possible with EMT. In addition, SRE is superior to EMT for its inversion applicability to determine the water saturation, S_w. Since the composite dielectric constant of a partially saturated porous medium is critically dependent on the amount of water present in the medium, an Average Water Content (AWC) equation was developed in this investigation which is a very compact expression and allows the determination of water content (θ_w) in an expeditious manner. The average dielectric constant used in this equation does not vary substantially for a broad range of different porous media. The AWC expression is a practical expression which can be directly applied in the field to determine the water content. The determination of the volume of water (V_w) from water content requires the knowledge of the total volume of the system (V_T). When more than two fluids saturate a porous medium, prediction of the dielectric constant becomes very complex and monitoring each fluid requires further investigation.

The current study has contributed to visualizing the possibility of employing the mixing laws in determining the composite dielectric constant of solutions and oil-in-water emulsions. Since the EMT formulation was originally derived for a dispersed system, the problem was how to apply the formula in the case of solutions because the two solvents (forming the solutions) were intermingled rather than one fluid is being dispersed in the other. In contrast, the dielectric measurements on O/W emulsion systems show good agreement with the EMT formulation, a conclusion which was expected because the original theory was derived for such systems. Although the O/W emulsion system appears to be a complex one, in that the oil droplets disposed in an aqueous phase are surrounded by negative ions, leading to an interaction between the dispersal droplets, that interaction is not strong enough to show any change in the dielectric measurements.

The failure of the most popular mixing laws to predict the measured values of solutions is not surprising because these mixing laws are not based on molecular models. The high measured values of the two polar fluids mixture (water and methanol) reflect an increased dipole moment resulting from the combination of both fluids. This "larger" value in the "net" dipole moment leads to the increase in the composite dielectric constant of the mixture.

Particular care must be taken when using consolidated samples which are fabricated to fit a coaxial transmission line, to account for the gaps and the filling fluids. The gap effect is very large if the inner radii are close enough so that there are irregularities in the space between the inner conduction at the radius of the inner hole of the rock sample. Unacceptably large errors can result if the correction formula is not used when measurements are made for consolidated materials, particularily with air measurements. As with unconsolidated samples, TQE produces satisfactory results for fully water saturated consolidated cores (sandstone), but not for partial saturation where the use of EMT and SRE mixing laws are recommended.

Application of microwave dielectric techniques to study the multiple fluid flow in porous media offers a promising means of characterizing both hydrological and retention characteristics of the system. Studying partial saturation and flow rate for both miscible and immiscible fluids in combination with water can provide information about characterizing medium properties which are pertinent to defining remedial measures in the event of an accidental spill of these materials, or the water flooding in the secondary recovery of oil wells. The retained volume caused by the spill or the flood can be determined from the porous medium retention of the fluid while the rates of flow of the multicomponent system can be monotored using the dielectric constant technique. In the specific examples considered in this investigation, carbontetrachloride was found to be retained by a dry sand five times less than crude oil. The retention of carbontetrachloride increased for a wet sand while that of crude oil decreased. It is the viscosity of the fluid and the relative permeablilty of the porous medium which control the flow rates. It was found that ottawa sand is neutrally-wet in the presence of water and carbontetrachloride and water-wet when introduced to oil and water. This coating made the retention of carbontetrachloride increase while that of crude oil decreased. Thus, the wetness of the sand is an important factor in determining the flow and storage of the immiscible fluid. Removal of the crude oil with a water - immiscible displacing solvent resulted in the same total amount of immiscible fluid being retained in the sand which was unaffected by further water floods. This displacement procedure simply substituted one immiscible component (crude oil) with another (cyclohexane). The addition of small amount of surfactant to the water increased the removal of crude oil slightly but did not affect the trapping of cyclohexane. When a miscible component such as methanol was added to the water, the ability to remove combinations of cyclohexane and crude oil was improved considerably. This characteristic of methanol is of special importance. The amphiphilic properties of the methanol give it a mediating influence between the different fluids which are immiscible. Since methanol can be totally flushed by water, it could be used in flushing techniques.

The dielectric measuring technique applied to monitor movement and retention of both miscible and immiscible components in determing the flow and storage of the immiscible fliuds was shown to offer unique advantages in observing flow phemomenan.

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APPENDIX A

COAXIAL TRANSMISSION LINE

Definition

A coaxial transmission line consists of two concentric circular cylinders of metal (with conductivity σ and skin depth δ). TEM mode is propagating along the transmission line. The electromagnetic wave propagates in the annual region between the coaxial conductors, and field outsideis zero.

Characteristic Impedance and Propagation Constant

The two main parameters which determine the coaxial line are the characteristic impedance, Z_0, and the propagation constant γ.

Characteristic Impedance

It is usually desirable to characterize TEM waves on a line in terms of their voltage and current waves because they are readily measurable quantitites. The characteristics impedance is expressed as the ratio between the voltage and the current flowing in one of the cylinders, and refered to as Z_0 (see Eg. 3.1).

Propagation Constant

Propagation constant is a measure of the phase shift and alternative along the line. It is a complex quantity given by

$$\gamma = \alpha + i\beta$$

where α is the attenuation in nepers per meter and β is the phase shift in radians per meter.

Infinitely Long Line

Consider a section for an infinitely long transmission line. Let a sinusoidal signal E_1 be imposed at the left hand terminal. Let E_x be the voltage a distance x down the line. E_x is related to E_1, by the propagation constant in the following manner.

$$E_x/E_1 = e^{-\gamma x} = e^{-\alpha x}\, e^{-i\beta} \qquad \text{(A-1)}$$

$e^{-\alpha x}$ is a real quantity and gets smaller as x increases. It expresses how much the signal is attenuated. The second term, $e^{-i\beta}$, is an imaginary exponenetial quantity which tells how much the phase of the voltage E_x lags th ephase of the voltage E_1. These two terms together completely define the phase and amplitude relations existing between voltage E_x and E_1. The propagation constant can be applied similarly to the current

$$\frac{I_x}{I_1} = e^{\partial x} \qquad \text{(A-2)}$$

then

$$\frac{E_x}{I_x} = \frac{E_1 e^{-\gamma x}}{I_1 e^{-\gamma x}} = Z_0 \qquad \text{(A-3)}$$

So, for an infinitely long line the voltage and the current are related to the characteristic impedance and the propagation constant by Equation A-3.

Matched Finite Line

With the concept of the infite line in mind, lines of finite length can be considered. Start with an infinitely long line and split it into two sections. This action produces a line of finite length on the left terminated by a line infinitely long on the right. In so far as the finite section on the left is conerned, there would be no difference in the voltage and in the current existing on it if the finite section to the right could be replaced by the exact equivalent of its impedance. This substitution can be made. The input impedance of an infinitely long line is Z_0. If the section of infinite line is replaced by Z_0 none of the conditions existing on the left-hand section of the finite length will be affected. If the line is considered to be lossless, placing Z_0 in the position of the infinitely long line section does not alter the system.This procedure is known as matched operation.

Finite Line with Arbitrary Load

In the above section we made the transmition from an infitely long line to one of finite length. This change produced a rather special case in which the finite section is terminated in its characteristic impedance. Of considerably more importance is a finite line with an arbitrary load. Note that in the special case of a finite line terminated in its characteristic impedance, the ratio of voltage to current at any point in the line was equal to Z_0, and that all the power the generator delivered into the line was absorbed in the load. Futhermore, in this special case the voltages and currents were being propagated only from the generator to the load. In other words, there was no signal traveling from right to left.

There is only one more condition to be added to permit handling of arbitrary load. Since the forward wave at all points on the transmission line maintains the ratio between E_i and I_i as Z_0, the wave meeting an impedance not equal to Z_0 can no longer support the same ratio between E_i and I_i. However, the addition of a signal traveling from righ to left permits the resulting voltage and current at that point to have the proper ratio, which is the impedance of the load. There are then two current and voltage waves on the line. They are defined as follows:

> Incident wave. The voltage or current being propagated from the generator towards the load. These waves will be denoted by the subscript i.
>
> Reflected Wave. The voltage or current being propagated from the load towards the generator. These waves will be denoted by the subscript r.

Since the relation between the reflected and incident waves is completely determined by the load and the line, distance will be measured from right to left with zero distance at the load. Voltages and currents at the load will be denoted by the subscript o, and voltages and currents at other points will be donoted by subscript x.

There is a definite relation between the reflected and incident waves. It is determined by the load and characteristic impedance of the line, called the voltage reflection coefficient ρ_v, the relation is defined as follows

$$\frac{E_{ro}}{Eio} = \frac{Z_L - Z_o}{Z_L + Z_o} = \rho_v \qquad \text{(A-4)}$$

The current reflection coefficient is

$$\frac{I_{ro}}{I_{io}} \quad \frac{Z_o - Z_L}{Z_o + Z_L} = \rho_i = -\rho_v \qquad \text{(A-4)}$$

Though the TEM mode is by far the most important, TE and TM modes are also capable of propagating along the line. The latter modes, however, are evansescent before their cutoff frequencies which occur for ordinary coaxial lines in the upper microwaver frequencies and beyond. The TE and TM modes on two-conductor lines thus have no useful applications to signal or power transmission.

APPENDIX B

DETERMINATION OF THE FLUID SATURATION

In this appendix, the derivation of the Equ 5.5, which calculate the fluid saturation (S_f) from three measurements of the dielectric constant. The general emperical formula is given by

$$\varepsilon_{fs} = [\varepsilon^c{}_f\, \phi + \varepsilon^c{}_s(1-\phi)]^{1/c} \qquad \text{(B-1)}$$

The matrix is assumed to be fully saturated by a fluid which has a dielectric constant ε_f. The porosity of the medium is ϕ. If the fluid is water, the A-1 can be written as

$$\varepsilon_{ws} = [\varepsilon^c{}_w\, \phi + \varepsilon^c{}_s(1-\phi)]^{1/c} \qquad \text{(B-2)}$$

If the porous medium is partially saturated with water (and partially with the fluid), then the composite dielectric constant (Meador and Cox, 1975) is given as

$$\varepsilon = [\varepsilon^c{}_w\, \phi\, S_w + \varepsilon^c{}_f\, \phi\, (1-S_w) + \varepsilon^c{}_s(1-\phi)]^{1/c} \qquad \text{(B-3)}$$

Eq. A-3 reflects the composite dielectric constant at any time during the flow, as long as only two fluids are present in the system. From Eqs. B-1 and B-2

$$\varepsilon^c{}_{ws} - \varepsilon^c{}_{fw} = (\varepsilon^c{}_w - \varepsilon^c{}_f)\, \phi \qquad \text{(B-4)}$$

And from Eqs. A-2 and A-3

$$\begin{aligned}\varepsilon^c{}_{ws} - \varepsilon^c &= (\varepsilon^c{}_w - \varepsilon^c{}_f)\, \phi - \phi\, S_w\, (\varepsilon^c{}_w - \varepsilon^c{}_f) \\ &= (\varepsilon^c{}_w - \varepsilon^c{}_f)\, \phi\, (1 - S_w)\end{aligned}$$

Then

$$1 - S_w = \frac{\varepsilon^c{}_{ws} - \varepsilon^c}{(\varepsilon^c{}_{ws} - \varepsilon^c{}_f)\, \phi}$$

But using Eq. (A-4);

$$1 - S_w = \frac{\varepsilon^c_{ws} - \varepsilon^c}{\varepsilon^c_{ws} - \varepsilon^c_f} \qquad \text{(B-5)}$$

From the begining it was assumed that the system pores contain only a fluid and water, therefore,

$$S_w + S_f = 1$$

or

$$S_f = 1 - S_w \qquad \text{(B-6)}$$

Substitution of Eq. A-6 into A-5 and using the exponent c = .75 (for the TQE);

$$S_f = \frac{\varepsilon^{.75}_{ws} - \varepsilon^{.75}}{\varepsilon^{.75}_{ws} - \varepsilon^{.75}_{fw}}$$

Which is the equation that determines the partial fluid saturation (S_f) from the dielectric measurements.

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