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DIELECTRIC MEASUREMENTS OF FIVE DIFFERENT SOIL TEXTURAL TYPES AS FUNCTIONS OF FREQUENCY AND MOISTURE CONTENT

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U.S. DEPARTMENT OF COMMERCE, Juanita M. Kreps, Secretary
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Open-circuit coaxial transmission-line sample holders were used to determine the electromagnetic dielectric properties of five soil textural types as functions of moisture level content and frequency. A brief outline of the theoretical basis is given for the open-circuit method along with the measurement system and the sample preparation. Experimental results are given for the different soil textural types for moisture levels ranging from 0 to 48 percent and for test frequencies ranging from 300 to 9300 MHz.

Key words: Attenuation; coaxial sample holder; density; dielectric properties; relative dielectric constant; soil textural types.

1. INTRODUCTION

This final report covers the results of measurements that were made on five soil textural types that included sand, sandy loam, silt loam, clay loam, and clay to determine their electromagnetic properties of permittivity (dielectric and attenuation constants) as functions of frequency and moisture content. The soils were prepared and furnished by Robert Falls of the U.S. Army Mobility Equipment Research and Development Center (MERDC) at Fort Belvoir, Virginia. The calculations were made from measurements of the propagation characteristics of 14 mm open-circuit coaxial transmission-line sample holders that were filled with the different soil types. The measurements were taken at test frequencies of 300, 500, 1000, 2000, 4000, and 9300 MHz for moisture levels ranging from 0 to 48 percent (of dry soil weight).

2. MEASUREMENT APPARATUS AND THEORY

2.1 Background

Transmission-line measurements of a dielectric sample terminated by either a short circuit or an open circuit are well known [1]. The coaxial open-circuit method used in the present work had been previously developed for measurements of lunar soil [2] and various grains [3] over wide frequency ranges. The open circuit has the advantage that the sample is easily inserted through the open end and that the results maintain essentially constant accuracy particularly at low frequencies. On the other hand, an offset coaxial short circuit can exhibit unacceptable errors at frequencies below 500 MHz. The sections below give a brief outline of the theoretical basis for the open-circuit method and are based on the theoretical development in reference [3].

2.2 Sample Holders

The measurement apparatus consists of open-circuit coaxial sample holders of the design illustrated in figure 1. The sample holders (fig. 2) were fabricated from 14 mm 50-ohm precision coaxial air-line stock and equipped with the type 900-BT precision coaxial connector assembly. The design allows the outer conductor to be unscrewed at the plane of the bead interface between sections 1 and 2--thus, allowing easy soil sample removal. A flat-faced teflon bead was used in place of the regular undercut connector bead to enable the bead interface to be in the same plane as that between sections 1 and 2. Typically with these connectors, the frequency region around 8.7 GHz should be avoided since the connector bead exhibits the characteristic to resonate over a very narrow band at this frequency.

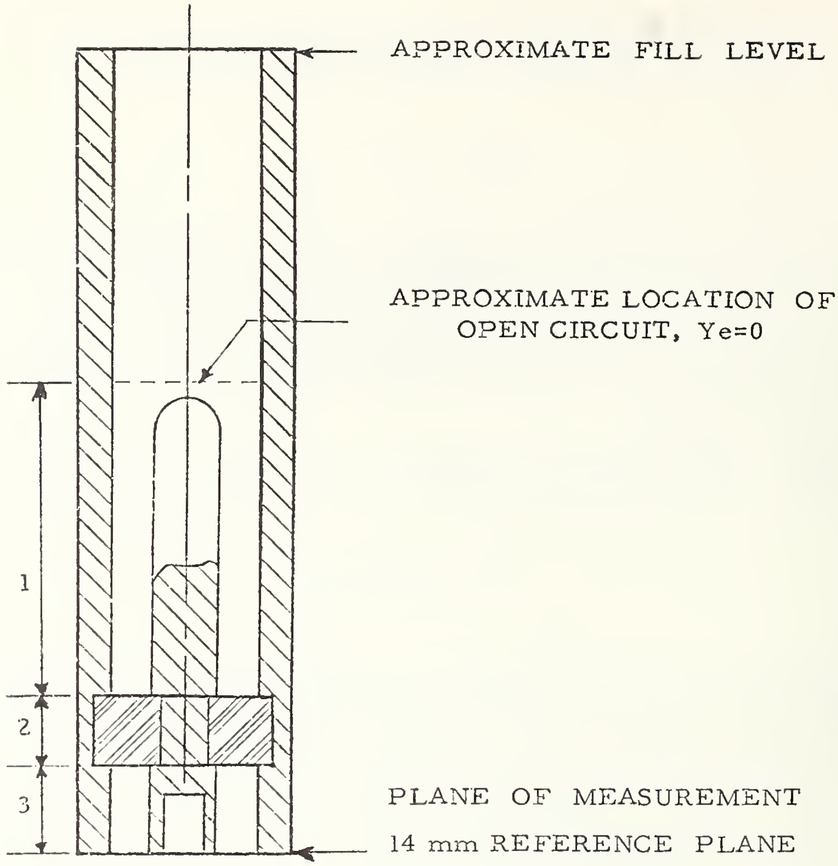

Figure 1. Cross section of open-circuit sample holder.

Figure 2. 14 mm open-circuit sample holders.

2.3 Theory of Electromagnetic Properties Determination

The sample holder is treated as a coaxial transmission line terminating in an open circuit. The effective location of the open circuit is somewhat beyond the end of the center conductor [4], as indicated in figure 1. The measurable quantity at the connector interface with the measuring instrument or at any transverse plane is the admittance, defined as the ratio of longitudinal current to transverse voltage for the TEM mode of a coaxial line. The admittance at the plane of measurement can be predicted theoretically by transforming the admittance from the plane of the open circuit of section 1 to the bottom of section 3. The input admittance Yin of a section is

$$\mathrm{Yin} = \mathrm{Yo}\left(\frac{\mathrm{Yo} + \mathrm{Ye}\coth\gamma d}{\mathrm{Ye} + \mathrm{Yo}\coth\gamma d}\right) \tag{1}$$

where the TEM characteristic admittance Yo is

$$\mathrm{Yo} = \frac{2\pi}{\ln b/a}\sqrt{\frac{\varepsilon_o \varepsilon^*}{\mu_o}} \tag{2}$$

and

γ = $\sqrt{-\omega\mu_o\varepsilon_o\varepsilon^*}$, the complex propagation constant in the section,

Ye = the admittance at the output end of the section,

d = length of the section under investigation,

a = inner conductor radius,

b = outer conductor radius,

ε_o = permittivity of free space,

ε^* = $\varepsilon'-j\varepsilon''$, the complex relative dielectric constant of the dielectric material in the section.

μ_o = magnetic permeability of free space,

ω = radian frequency.

It should be noted that both Yo and γ depend upon the complex permittivity ε^* of the section. Since there are three sections to the sample holder, eq. (1) is applied three times to transform the admittance from the plane of the open circuit of section 1, through section 2, and finally, to the bottom of section 3 to obtain the theoretical admittance. The admittance at a dielectric interface is continuous except when changes in radii a and b occur. Then the shunt admittance of the step $Y_{step} = j\omega C_{step}\varepsilon^*$ must be added. This is the case for section 2. C_{step}, the capacitance with air, is obtained from reference [5]. In theory, once calculated, sections 3 and 2 are known invariant sections whose admittances do not change with the addition of an unknown dielectric in section 1.

To obtain the electromagnetic properties of dielectric constant and loss of an unknown dielectric in section 1 from the measured admittance Ym, eq. (1) is used with Ye = 0 at the plane of the effective open i.e., $d = d_1 + d'$ where d' is the added distance [4] beyond the end of the center conductor to the effective open. With Ye = 0, eq. (1) reduces to

$$\mathrm{Yin} = \mathrm{Yo}\tanh\gamma d\ . \tag{3}$$

To solve eq. (3), the admittance value for Yin must be determined and is obtained from the measured admittance Ym of section 3 by transforming Ym backward from the measurement plane through the known invariant sections 3 and 2, using eq. (1), to the input of section 1. The transformed admittance Y'm which is Ym transformed to the input of section 1, becomes the admittance value required for Yin. Therefore, eq. (3) can now be solved and

$$Y'm = Yin = Yo \tanh \gamma d \tag{4}$$

where the complex unknown dielectric ε^* appears both in Yo and in γ. To find a solution, an estimate is given for ε^* in eq. (4), and iterated by Newton's method [6] until the equation is satisfied. The equation has multiple roots but at low frequencies (100 MHz) with soil dielectric, only the lowest root is reasonable. For higher frequencies, the previous low frequency value for ε^* furnishes the first estimate for the Newton method.

To check that the theoretical admittance equation correctly characterized the sample holder, the sample holder was measured with a known dielectric (air) in section 1. The measured admittance Ym verified that all measured quantities, e.g., section lengths, dielectric constants, Yo and Y_{step} were correct.

2.3.1 Center Conductor Correction For Electric Field Extension

To compensate for the center conductor with hemispherical end rather than flatly truncated center conductor, a correction is required for d_1 in eq. (4). The assumption is made that the terminating capacitance [5] and the equivalent extension [4] is still just the same as with the flat ended conductor. Therefore, a small quantity is subtracted from the physical length d_1 of section 1. The amount subtracted is approximately 21 percent of the radius of the center conductor. This method [3] was found to be valid experimentally based upon measurement results of known materials e.g., air and carbon tetrachloride, when measured using both a hemispherical and a flat ended center conductor.

The electric field which extends beyond the end of section 1 interacts with the dielectric sample and contributes to the measured admittance Ym. This is correctly taken into account in the above method. Not only does γ contain ε^* but also the extended distance d' in d was updated during the Newton iterations to be correct for the current value of ε'. A correction for the loss ε'' was not used. More work is required to find the effect of ε''.

Finally, since the field extends beyond the end of the center conductor, a calculation is required to determine how far the soil sample should extend. Theoretically, it should extend to infinity. Practically, if the outer conductor is well below cutoff, i.e.,

$$\varepsilon' \ll \left(\frac{0.387\nu}{bf}\right)^2 \tag{5}$$

where

f = the frequency in hertz,

b = outer conductor radius,

ν = velocity of light with same units as length,

then the sample needs to extend beyond the center conductor at least a distance of 1.5 b. The evanescent field in the outer conductor decays as exp (-2.405 z/b) where z is the distance beyond the end of the center conductor.

3. MEASUREMENT APPROACH

3.1 Measurement System

The electromagnetic properties (dielectric constant and attenuation) of the soil samples were obtained from the measured admittance as described in section 2.2. The admittance, in turn, was obtained by measuring the input reflection coefficient Γ of the holder with its sample at the plane of the connector (input of section 3) by an Automatic Network Analyzer (ANA). The ANA is a computerized microwave measurement system capable of making high-quality measurements of complex scattering parameters at discrete frequencies up to 18 GHz. The ANA calibration is conducted at the connector plane of interest (in this case, the 14 mm reference plane) using high-precision short-circuit elements and a 50-Ω sliding termination or a high value return loss (greater than 50 dB) 50-Ω termination. A large capacity computer was used to reduce the measurement data to obtain mean and standard deviation values for dielectric constant, loss tangent, attenuation and density.

3.2 Sample Preparation

Each soil sample was oven dried for approximately one hour at 120°C and at 10 minute intervals until no weight difference could be detected. This procedure was used to establish the dry soil weight condition of 0 percent moisture content. To achieve the various moisture level conditions, the desired weight of distilled water was added and thoroughly mixed into the dry weight sample. The moist sample was carefully packed into the open-circuit sample holder by means of a nylon plunger. A hand held vibrator, placed at the base of the sample holder, was helpful in packing the dry weight soil samples.

To help establish a higher degree of confidence in the results of the electromagnetic measurements, three sample holders and like samples were prepared and measured for each moisture level condition at each frequency. Results show that the standard deviation from the mean value for density didn't vary between samples by more than a few hundredths gram/cc. It should also be noted that there was less than 0.1 percent weight difference between the initial and final weight measurements of the same sample.

3.2.1 Soil Texture Construction

The basic elements that are used in soil texture contruction are grains of sand, clay, and silt which are defined as:

Sand - Washed quartz grains between diameters of 0.60 millimeters and 0.027 millimeters;
Silt - Washed quartz grains (mica all right) between diameters of 0.021 millimeters and 0.0033 millimeters;
Clay - Inorganic clay such as Kaolin or Bentonite or a mixture of both, such that plate diameters are below 0.0033 millimeters.

The five soil textural types as prepared by MERDC were described as being constructed from the basic elements as follows:

Sand Texture - 9.5 parts sand, 0.5 parts clay, and 0.3 parts silt;
Sandy Loam - 6.4 parts sand, 3.6 parts clay, and 2.5 parts silt;
Silt Loam Texture - 2.0 parts sand, 8 parts clay, and 6.8 parts silt;
Clay Loam Texture - 3.2 parts sand, 6.8 parts clay, and 3.3 parts silt;
Clay Texture - 2.0 parts sand, 8 parts clay, and 2 parts silt.

Classification of the soil types according to particle size and distribution are illustrated on the soil textural triangle as shown in figure 3.

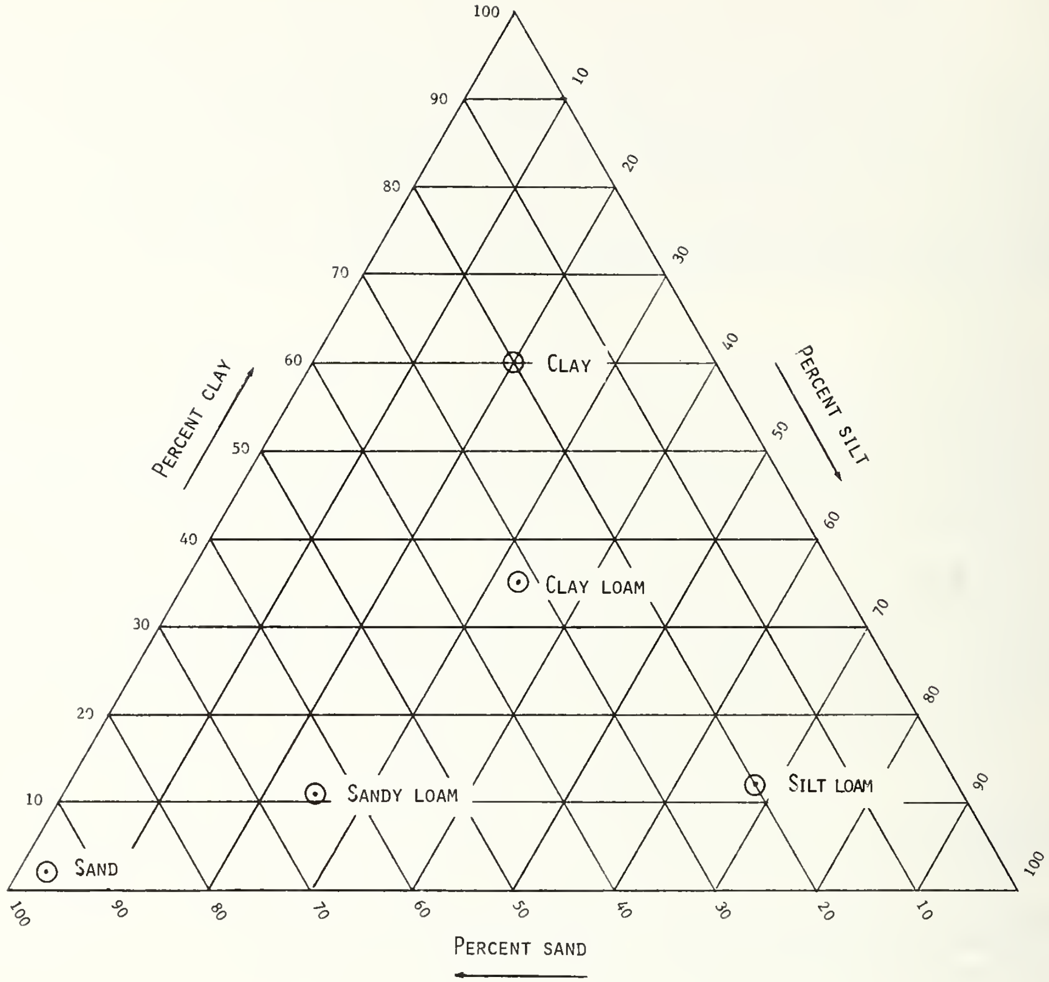

Figure 3. Classification of each soil textural type on the U. S. Department of Agriculture soil triangle.

4. EXPERIMENTAL RESULTS

Tables 1 thru 5 show the experimental results of mean value and standard deviation from the mean value for density, relative dielectric constant, and attenuation obtained from measurements made on samples of five different soil textural types as functions of frequency and moisture content.

A plot of the magnitudes of relative dielectric constant ε' and attenuation for silt loam as a function of moisture content level and frequency is given in figure 4. This plot is representative of the other four soil texture types and is given to show the shift in ε' and attenuation that occurs with the higher moisture content levels starting at approximately 10 percent. Depending upon the soil textural type and moisture content, this shift or "window" seems to appear at approximately 800 MHz and levels off around 1400 MHz.

Table 1.

Experimental results of mean value and standard deviation (sd) from the mean value for density, relative dielectric constant, and attenuation obtained from measurements made on samples of sand texture for moisture levels of 0, 1, 2, 4, 8, and 14 percent.

Sand - 0%

(Mean density = 1.540; sd = .022 g*/cc)
*gram/cubic centimeter

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	2.702	.0486	-.00372	.0002
500	2.694	.0492	-.00206	.00006
1000	2.693	.0515	.00161	.0004
2000	2.695	.0515	.00833	.0003
4000	2.656	.0419	.0836	.004
9300	2.737	.0660	.240	.02

Sand - 1%

(Mean density = 1.614; sd = .014 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	3.227	.0352	.0503	.001
500	3.131	.0299	.0680	.002
1000	3.062	.0182	.0968	.0006
2000	3.015	.0112	.136	.001
4000	2.914	.0068	.304	.002
9300	3.037	.0132	.640	.05

*Sand - 2%

*(Mean density = 1.455; sd = .015 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	3.072	.043	.0705	.002
500	2.977	.032	.0892	.003
1000	2.930	.036	.113	.003
2000	2.915	.079	.139	.009
4000	2.891	.083	.340	.02
9300	2.905	.038	.789	.03

Sand - 4%

(Mean density = 1.583; sd = .020 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	4.225	.168	.173	.01
500	4.079	.162	.197	.01
1000	4.019	.165	.231	.01
2000	3.940	.142	.287	.03
4000	3.946	.148	.607	.02
9300	3.373	.198	1.38	.32

*Note: The lower density probably caused the ε' values to be lower than those for sand-1%.

Sand - 8%

(Mean density = 1.732; sd = .016 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	6.957	.235	.249	.007
500	6.792	.249	.278	.01
1000	6.708	.300	.335	.02
2000	6.533	.128	.535	.02
4000	6.425	.196	1.27	.07
9300	5.854	.231	2.86	.18

Sand - 14%

(Mean density = 1.732; sd = .015 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	10.458	.413	.251	.01
500	10.641	.415	.296	.01
1000	11.179	.349	.429	.04
2000	9.951	.334	.693	.05
4000	10.544	.441	1.80	.24
9300	10.179	1.14	3.38	1.0

Table 2.

Experimental results of mean value and standard deviation (sd) from the mean value for density, relative dielectric constant and attenuation obtained from measurements made on samples of sandy loam texture for moisture levels of 0, 1.5, 3, 6, 12, and 24 percent.

Sandy Loam - 0%

(Mean density = 1.435; sd = .008 g*/cc)
*gram/cubic centimeter

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	2.650	.040	-.00195	.00008
500	2.642	.047	.00081	.0001
1000	2.660	.079	.00762	.0004
2000	2.680	.102	.00820	.002
4000	2.691	.125	.102	.01
9300	2.663	.027	.166	.09

Sandy Loam - 1.5%

(Mean density = 1.410; sd = .004 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	3.791	.008	.124	.001
500	3.548	.010	.177	.001
1000	3.341	.020	.277	.004
2000	3.243	.020	.393	.002
4000	3.023	.034	.743	.02
9300	3.236	.065	1.58	.06

Sandy Loam - 3%

(Mean density = 1.402; sd = .022 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	3.954	.067	.135	.004
500	3.690	.053	.194	.004
1000	3.464	.052	.308	.006
2000	3.278	.039	.412	.02
4000	3.174	.106	.798	.02
9300	3.190	.045	1.65	.08

Sandy Loam - 6%

(Mean density = 1.547; sd = .012 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	5.967	.076	.406	.005
500	5.407	.062	.520	.004
1000	4.909	.028	.723	.01
2000	4.408	.035	.913	.04
4000	4.301	.019	1.43	.06
9300	3.813	.084	3.42	.36

Sandy Loam - 12%

(Mean density = 1.650; sd = .044 g/cc)

Frequency MHz	Rel. Diel. Constant		Attenuation - dB/cm	
	Mean	sd	Mean	sd
300	10.063	.534	.985	.1
500	9.164	.681	1.16	.1
1000	7.759	.699	1.40	.2
2000	8.148	.555	2.33	.2
4000	7.551	1.294	3.14	.1
9300	"erroneous data"			

Sandy Loam - 24%

(Mean density = 1.928; sd = .024 g/cc)

Frequency MHz	Rel. Diel. Constant		Attenuation - dB/cm	
	Mean	sd	Mean	sd
300	24.527	.326	1.88	.002
500	24.328	.185	2.11	.002
1000	22.705	.625	2.71	.04
2000	21.156	1.072	3.51	.56
4000	16.549	1.56	4.27	.91
9300	9.884	2.4	9.57	2.5

Table 3

Experimantal results of mean value and standard deviation (sd) from the mean value for density, relative dielectric constant and attenuation obtained from measurements made on samples of silt loam texture for moisture levels of 0, 2.5, 5, and 10 percent.

Silt Loam - 0%

(Mean density = 1.106; sd = .037 g*/cc)
*gram/cubic centimeter

Frequency MHz	Rel. Diel. Constant		Attenuation - dB/cm	
	Mean	sd	Mean	sd
300	2.340	.049	.00325	.0002
500	2.321	.051	.00771	.0004
1000	2.318	.059	.0188	.0009
2000	2.343	.085	.0351	.003
4000	2.325	.044	.103	.004
9300	2.408	.094	.188	.019

Silt Loam - 2.5%

(Mean density = 1.133; sd = .043 g/cc)

Frequency MHz	Rel. Diel. Constant		Attenuation - dB/cm	
	Mean	sd	Mean	sd
300	3.137	.029	.102	.002
500	2.959	.025	.140	.002
1000	2.812	.018	.205	.001
2000	2.728	.016	.270	.005
4000	2.646	.018	.519	.02
9300	2.660	.052	.958	.04

Silt Loam - 5%

(Mean density = 1.267; sd = .017 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	4.453	.097	.214	.007
500	4.038	.083	.301	.009
1000	3.692	.078	.467	.03
2000	3.391	.080	.589	.02
4000	3.319	.108	1.17	.10
9300	3.170	.092	2.30	.12

Silt Loam - 10%

(Mean density = 1.435; sd = .010 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	9.151	.186	.675	.02
500	8.083	.182	.903	.04
1000	7.458	.343	1.25	.07
2000	5.573	.157	1.82	.10
4000	5.275	.048	2.45	.50
9300	4.065	.268	6.83	1.3

Table 4

Experimental results of mean value and standard deviation (sd) from the mean value for density, relative dielectric constant, and attenuation obtained from measurements made on samples of clay loam texture for moisture levels of 0, 1, 3, 6, 12, 24, and 48 percent.

Clay Loam - 0%

(Mean density = 1.266; sd = .035 g*/cc)
*gram/cubic centimeter

Frequency	Rel. Diel. Constant		Attenuation - dB/cm	
MHz	Mean	sd	Mean	sd
300	2.775	.024	.00229	.00007
500	2.760	.027	.00625	.00006
1000	2.773	.037	.0167	.0002
2000	2.771	.051	.0289	.007
4000	2.758	.048	.185	.04
9300	2.708	.076	.404	.21

Clay Loam - 1%

(Mean density = 1.311; sd = .010 g/cc)

Frequency	Rel. Diel. Constant		Attenuation - dB/cm	
MHz	Mean	sd	Mean	sd
300	3.265	.050	.074	.001
500	3.131	.048	.101	.001
1000	3.045	.041	.144	.001
2000	3.008	.037	.197	.009
4000	2.915	.064	.472	.04
9300	2.989	.141	.732	.03

Clay Loam - 3%

*(Mean density = 1.235; sd = .022 g/cc)

Frequency MHz	*Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	3.402	.061	.123	.004
500	3.175	.056	.169	.005
1000	2.962	.066	.248	.01
2000	2.824	.100	.344	.02
4000	2.759	.055	.708	.06
9300	2.784	.048	1.29	.07

Clay Loam - 6%

(Mean density = 1.436; sd = .035 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	5.667	.047	.283	.007
500	5.108	.023	.387	.007
1000	4.649	.101	.568	.003
2000	4.151	.065	.761	.06
4000	4.024	.156	1.14	.10
9300	3.826	.122	2.31	.73

*Note: The lower density probably caused the ε' values to be lower than those for clay loam-1%.

Clay Loam - 12%

(Mean density = 1.468; sd = .018 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	8.719	.183	.689	.02
500	7.734	.138	.926	.03
1000	7.363	.223	1.43	.13
2000	5.702	.018	1.66	.08
4000	5.682	.005	2.26	.02
9300	4.657	.418	3.85	.68

Clay Loam - 24%

(Mean density = 1.920; sd = .021 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
9300	14.283	.324	15.46	2.32

Clay Loam - 48%

*(Density = 1.641 g/cc)

Frequency MHz	*Rel. Diel. Constant	Attenuation dB/cm
9300	9.75	38.95

*Note: The lower density probably caused the values for ε' to be lower than that for clay loam-24%.

Table 5

Experimental results of mean value and standard deviation (sd) from the mean value for density, relative dielectric constant and attenuation obtained from measurements made on samples of clay texure for moisture levels of 0, 1, 3.5, 7, and 14 percent.

Clay - 0%

(Mean density = 1.174; sd = .040 g*/cc)
*gram/cubic centimeter

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	2.717	.052	.00455	.0003
500	2.703	.053	.00933	.0004
1000	2.721	.065	.0213	.0005
2000	2.721	.068	.0346	.008
4000	2.732	.105	.180	.02
9300	2.677	.052	.271	.03

Clay - 1%

(Mean density = 1.173; sd = .016 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	Rel. Diel. Constant sd	Attenuation - dB/cm Mean	Attenuation - dB/cm sd
300	3.038	.022	.0782	.001
500	2.902	.023	.106	.002
1000	2.806	.032	.154	.006
2000	2.745	.049	.211	.009
4000	2.652	.034	.443	.05
9300	2.728	.185	.830	.09

Clay - 3.5%

(Mean density = 1.233; sd = .096 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	3.877	.061	.158	.004
500	3.612	.050	.216	.005
1000	3.444	.034	.326	.007
2000	3.276	.039	.385	.02
4000	3.149	.059	.844	.05
9300	3.077	.179	1.32	.27

Clay - 7%

(Mean density = 1.376; sd = .007 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	6.030	.034	.334	.005
500	5.399	.015	.459	.005
1000	4.952	.058	.702	.004
2000	4.187	.005	.813	.03
4000	4.289	.085	1.38	.20
9300	3.754	.053	2.41	.43

Clay - 14%

(Mean density = 1.444; sd = .024 g/cc)

Frequency MHz	Rel. Diel. Constant Mean	sd	Attenuation - dB/cm Mean	sd
300	10.676	.204	.766	.04
500	9.402	.186	1.08	.06
1000	9.871	.807	1.44	.05
2000	6.294	.124	2.00	.08
4000	5.642	.823	3.83	1.2
9300	5.185	.950	7.72	2.5

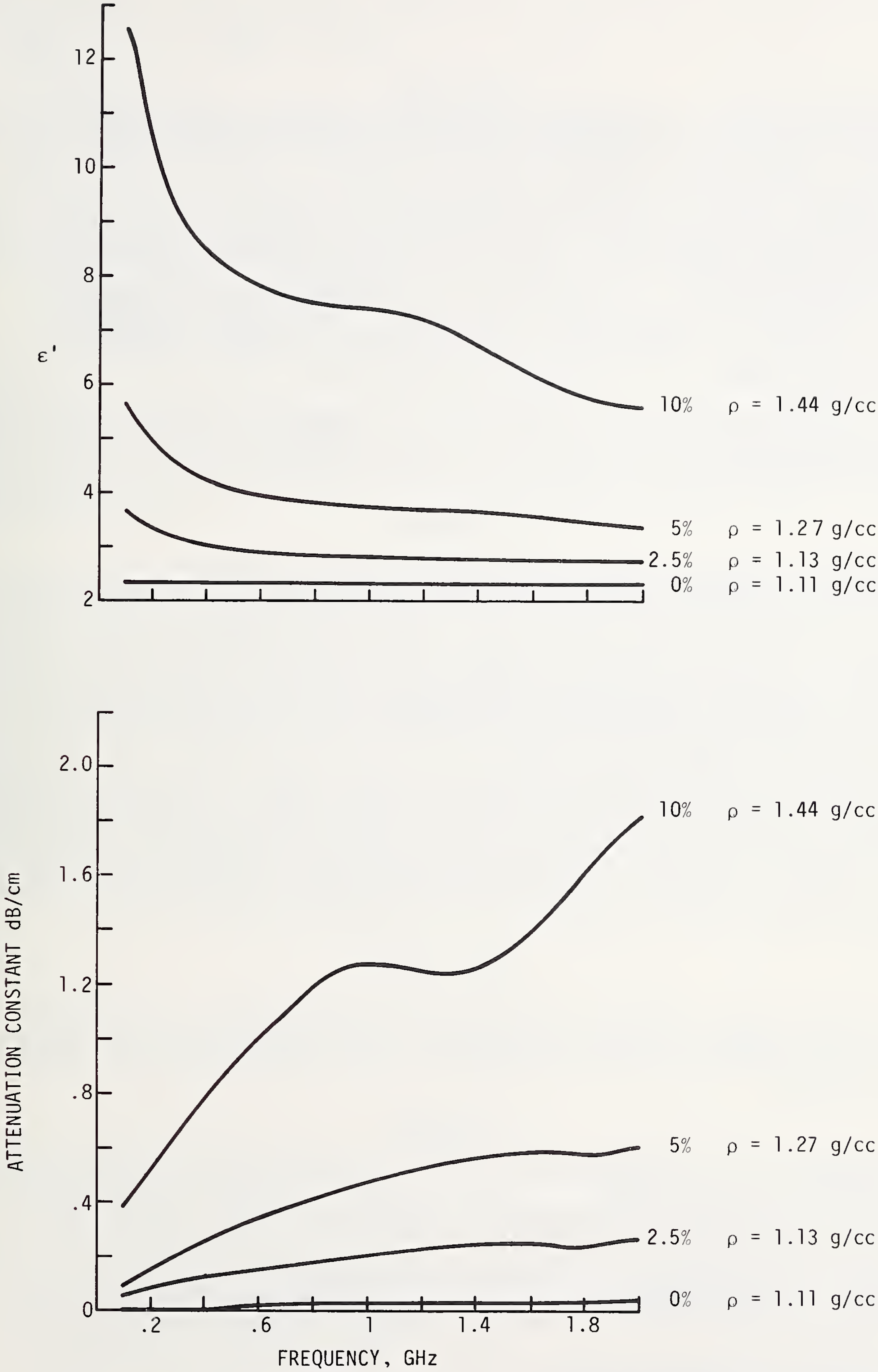

Figure 4. Plot of the magnitudes of ε' and attenuation of silt-loam as a function of frequency and moisture content.

5. DATA SUMMARY

A few of the high-moisture content levels that were requested by MERDC could not be furnished at this time. This included the moisture levels of 20 and 40 percent for the silt loam (table 3), the moisture levels of 24 and 48 percent for the clay loam (table 4), and the moisture levels of 28 and 56 percent for the clay (table 5). However, results for the moisture levels of 24 and 48 percent for clay loam were obtained at 9.3 GHz and were included in table 4. These high-moisture level measurements were achieved by using a WR-90 rectangular-waveguide offset short-circuit sample holder. Similar high-moisture level measurements employing the WR-90 sample holder were also made on the silt loam and the clay, but the results were found to be inconclusive. Two 14 mm short-circuit coaxial sample holders were also used in our experiment to investigate the effects of the high moisture levels on the three soil textural types at the lower frequencies down to 500 MHz. It was found that verification of measurement results was difficult to achieve and were not included in this report.

It should be emphasized that the values that were obtained for the relative dielectric constant results in tables 1-5 are a function of sample density. In general, the larger the sample density, the larger the value for relative dielectric constant. For example, see the results for sand-1% and sand-2% in table 1.

6. CONCLUSIONS

A technique describing a three-section, open-circuit sample holder has been presented that accurately obtains the electromagnetic dielectric properties of low-loss soil (< 20% moisture level constant) by automated measurement techniques. Experimental results were obtained for five soil textural types that were measured in the open-circuit sample holders as a function of frequency and moisture content. A few of the high moisture content levels could not be achieved at this time because these are high-loss dielectric materials. The main errors occur when the loss tangent is greater than zero, thus, allowing higher order modes to be propagated. With the open-circuit sample holder, saturated dirt cannot be accurately measured with the center conductor covered at frequencies above 3 to 4 GHz and with high losses 1 to 2 GHz could be a limit.

However, the problem of high-loss dielectric materials could be solved if some effort was devoted to a larger program that addressed this as one of the objectives. Future experiments would include the gathering of a data base that would characterize the better known soil types as a function of frequency, moisture content, and density. Sample holders need to be studied and modified, and a proper mathematical model derived which is general enough to properly describe the sample holder for accommodating high-loss dielectric materials.

7. ACKNOWLEDGMENT

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Open-circuit coaxial transmission-line sample holders were used to determine the electromagnetic dielectric properties of five soil textural types as functions of moisture level content and frequency. A brief outline of the theoretical basis is given for the open-circuit method along with the measurement system and the sample preparation. Experimental results are given for the different soil textural types for moisture levels ranging from 0 to 48 percent and for test frequencies ranging from 300 to 9300 MHz.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*

Attenuation; coaxial sample holder; density; dielectric properties; relative dielectric constant; soil textural types.

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