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ELECTROMAGNETIC ATTENUATION PROPERTIES OF CLAY AND GRAVEL SOILS

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FOREWORD

In response to a request from the Air Force Weapons Laboratory(AFWL) the National Bureau of Standards undertook a project to investigate the microwave penetrability of selected pavement materials. The overall objective of the AFWL was to establish the feasibility of using active microwave techniques to differentiate layers in a pavement system and to accurately measure the thickness of each layer for a variety of soil types and moisture conditions. Layer thickness measurements are needed to complement a field operational method currently being developed by AFWL to nondestructively evaluate the condition and load-carrying capacity of airfield pavements.

This initial effort consisted of investigating the relationship between microwave penetrability in clay and gravel soils as a function of moisture content and microwave frequency.

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ABBREVIATIONS AND SYMBOLS

dBm	Signal level with respect to 1 mW, decibels
E_{in}	Incident electric intensity, v/m
E_r	Reflected electric intensity, v/m
G_s	Average specific gravity of soil solids
S	Degree of saturation
c	Velocity of light in free space, m/sec
e	Natural logarithm base
f	Frequency, Hz
i	1, 2 for media 1 and 2 respectively
ℓ_2	Sample depth, m
t	time, sec.
Γ	Reflection coefficient of infinitely thick sample
Γ_{in}	Reflection coefficient of finite thickness sample
Γ_m	Maximum reflection coefficient of finite thickness sample
α_i	Attenuation constant, nepers/m
β_i	Phase constant, radians/m
γ_i	Propagation constant
γ_d	Dry density, g/cm^3
γ_m	Wet density, g/cm^3
δ	Skin depth, m
ε_i	Permittivity, farad/m
ε_i'	Permittivity relative to free space, farad/m
μ_i	Permeability, henry/m
σ	conductivity, mho/m
ω	Angular velocity, radians/sec
η	Intrinsic impedance, ohm

The objective of this work was to establish the feasibility of using active microwave techniques to differentiate between the different subsurface layers in a pavement system. The electromagnetic attenuation properties of clay and gravel soils were measured as a function of moisture content and frequency. Measurements were done at frequencies in the 0.5 - 4.5 GHz range. Soil samples were compounded in the laboratory at approximately 10, 50 and 90% saturation. Sample thickness was in the range 2.5 - 20.3 cm. Each homogeneous sample was sealed in a polyethylene container to retain the total moisture and to maintain a constant moisture content with depth.

KEY WORDS: Attenuation; clay; gravel; measurements; microwave; skin depth.

1. INTRODUCTION

When using active microwave techniques to characterize natural construction materials, three factors are of prime importance: soil type, moisture content or saturation of the soil, and frequency of the microwave signal. Demonstration of the capability to distinguish between, and measure thickness of various pavement layers first requires a demonstration of the ability of microwave signals to penetrate a homogeneous layer of pavement material.

This effort consisted of investigating the relationship between soil penetrability as a function of soil type, moisture content, and microwave frequency. Measurements were made on clay and gravel soils having saturation of approximately 10%, 50%, and 90%, and at microwave frequencies in the range 0.5 - 4.5 GHz. The skin depth was determined for all soil type/frequency/saturation combinations.

All test samples were compounded in the laboratory. The surface area of all samples was 1.22m x 1.22m. After preparation, each sample was sealed in a polyethylene bag to retain total moisture content and to maintain a uniform moisture content within the layer.

2. THEORETICAL MODEL

The following equations outline the properties of a complex medium (see ref 1). In general, waves propagating in a medium undergo attenuation and phase shift. The complex propagation constants for plane waves is:

$$\gamma = j\omega\sqrt{\mu\varepsilon}\left[1-j\,\frac{\sigma}{\omega\varepsilon}\right]^{\frac{1}{2}} \tag{1}$$

and can be written as

$$\gamma = \alpha(\omega) + j\beta(\omega) \tag{2}$$

Solving for $\alpha(\omega)$ and $\beta(\omega)$ gives

$$\alpha(\omega) = \left\{\frac{\omega^2\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]\right\}^{\frac{1}{2}} \tag{3}$$

$$\beta(\omega) = \left\{\frac{\omega^2\mu\varepsilon}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]\right\}^{\frac{1}{2}} \tag{4}$$

which for small losses $(\frac{\sigma}{\omega\varepsilon} << 1)$ become,

$$\alpha(\omega) \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}} \tag{5}$$

$$\beta(\omega) \approx \omega\sqrt{\mu\varepsilon} \tag{6}$$

The intrinsic impedance of a medium is given by

$$\eta = \sqrt{\frac{\mu}{\varepsilon(1-j\frac{\sigma}{\omega\varepsilon})}} \tag{7}$$

The model used consisted of one layer of finite thickness of the material under test, sandwiched between air and an aluminum sheet (fig. 1). The medium is assumed to be isotropic and homogeneous with parallel plane boundaries. Electrical properties of the layer are described by permeability (μ), permittivity (ε), and conductivity (σ). The layer is assumed non-magnetic ($\mu = \mu_0$, where $\mu_0 = 4\ (10)^{7}$ H/m). Additionally, ε is assumed to be independent of frequency. Ray paths for electromagnetic energy are also assumed.

Due to the directivity of the ideal horns assumed in the model, only reflected waves are received. In practice, considerable design placement and polarization strategy are required to reduce the direct coupling to an acceptable level. The horns used were not ideal; however a single ray normal incidence model was used.

The input reflection coefficient in medium 1 for a single layer in a perfect conductor can be written as (see ref 1),

$$\Gamma_{in} = \frac{\Gamma_1 - e^{-2\gamma_2 \ell_2}}{1 - \Gamma_1 e^{-2\gamma_2 \ell_2}} \tag{8}$$

where Γ_1 is the reflection coefficient of a semi-infinite medium and is approximately given by

$$\Gamma_1 = \frac{1 - \sqrt{\varepsilon'_2}}{1 + \sqrt{\varepsilon'_2}} \tag{9}$$

and γ_2 by (2), (3) and (4). The magnitude of Γ_{in} will go through successive maxima and minima as a function of frequency, layer thickness, dielectric constant and loss. Minima (or maxima) will occur approximately every 2π radians. Thus, when ω is varied, successive minima occur when

$$2(\Delta\beta_2)\ell_2 = 2\pi \tag{10}$$

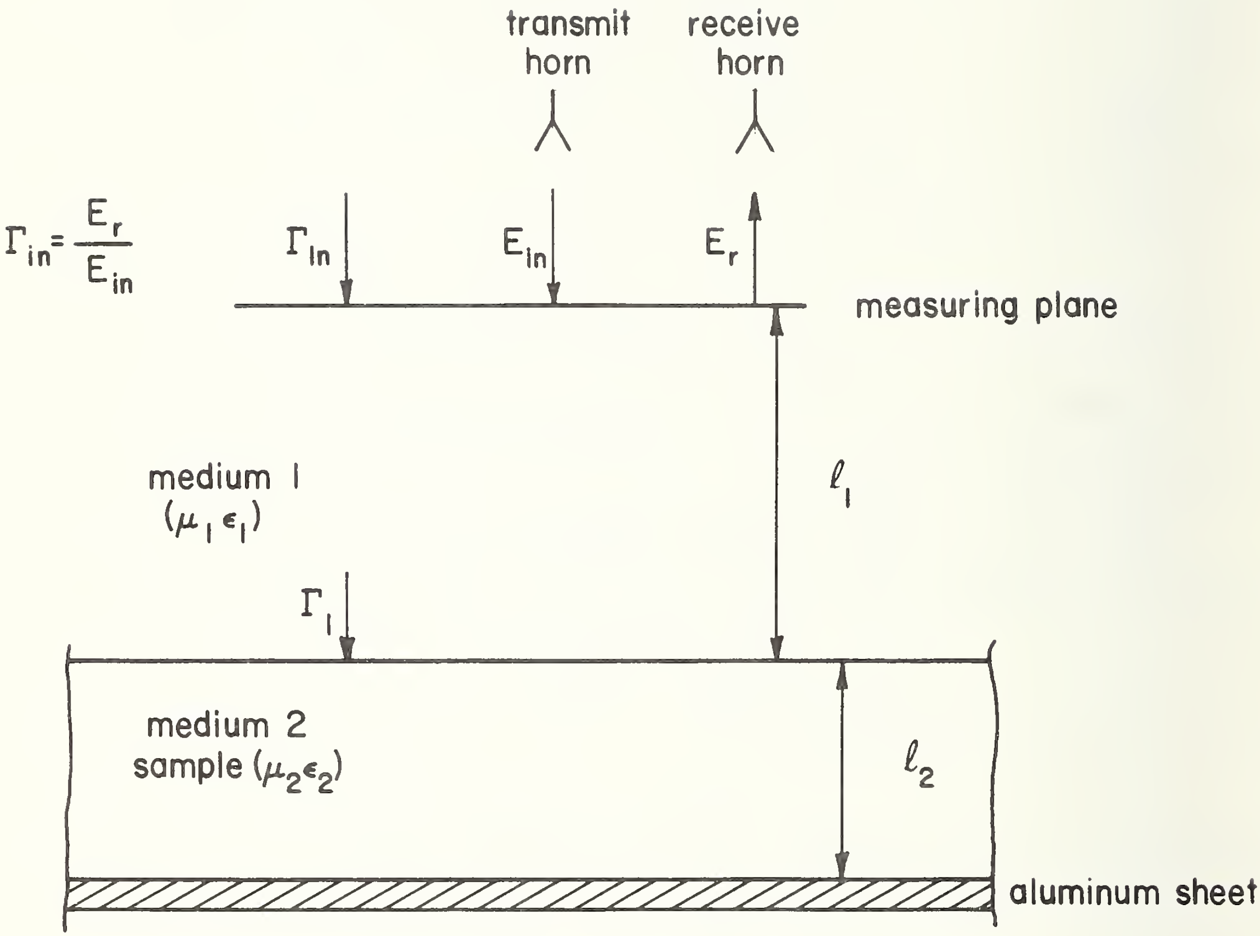

Figure 1. Plane waves normally incident on a plane dielectric boundary

from which

$$\sqrt{\varepsilon'_2} = \frac{c}{2\ell_2(f_2 - f_1)} \tag{11}$$

where successive minima occur at frequencies f_1 and f_2.

It has been shown (see ref 2) that an approximate expression for the maxima of Γ_{in} can be obtained when $\cos 2\beta_2\ell_2 = 1$. Equation (8) then becomes

$$\Gamma_m = \frac{\Gamma_1 - e^{-2\alpha_2\ell_2}}{1 - \Gamma_1 e^{-2\alpha_2\ell_2}} \quad , \tag{12}$$

and solving for the attenuator factor, obtain

$$-2\alpha_2\ell_2 = \ell n \left[\frac{\Gamma_1 - \Gamma_m}{1 - \Gamma_1\Gamma_m}\right] \quad . \tag{13}$$

Because $\varepsilon'_2 > 1$ the reflection Γ_1 as given in (9) will always be negative, thus the coefficient Γ_m as given in (12) is also negative. Because $|\Gamma_m| \geq |\Gamma_1|$, logarithms of positive numbers are involved.

Figure 2 shows how the reflection coefficients in this model are related. $|\Gamma_1|$ and $|\Gamma_{in}|$ are deduced from measurements. $|\Gamma_1|$ is determined by using frequencies f_1 and f_2 in (11). $|\Gamma_{in}|$ is determined by return loss measurement techniques (see ref 3). The sample thickness is constant; thus the attenuation of the sample can be determined from (13).

Skin depth is defined as the depth at which the wave has been attenuated to 1/e of its original value. Thus, skin depth, δ, can be determined from the relation

$$\alpha_2\delta = 1 \quad . \tag{14}$$

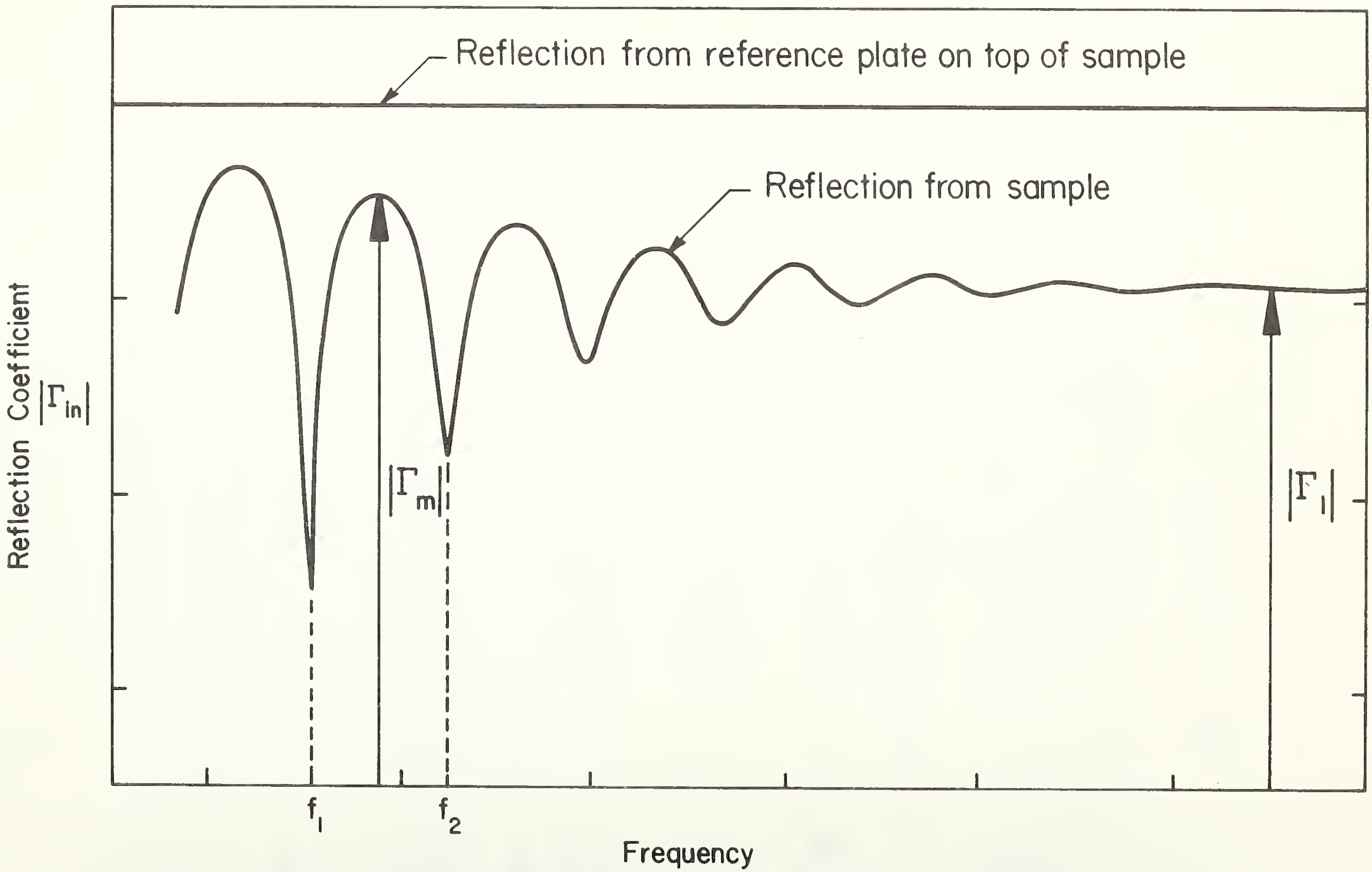

Figure 2. Reflection coefficient relationship

3. PREPARATION OF SOIL SAMPLES

3.1 Gravel

The gravel was blended by mixing coarse and fine concrete aggregates in calculated proportions, so that the grain-size distribution curve as shown in figure 3 was obtained. Soil so prepared classifies as a poorly graded gravel (GP) in the Unified Soil Classification system (see ref 4). Compaction characteristics were obtained by the modified Proctor method and are given in figure 4. From figure 4, a moisture content was selected for compacting soil in the test bed in order to achieve a compacted degree of saturation of approximately 10%. The actual degree of saturation of the test soil (based on volume calculations) could not be accurately predicted until the beds had been prepared.

Mixing of the dry gravel with the water was carried out in a concrete mixer, and compaction of the bed was by means of a gasoline-powered vibratory compactor, assisted by hand compaction. After compaction, the box and its compacted contents were weighed by supporting it on a knife edge on one side and two proving rings on the opposite side. Thus, with the wet density, moisture content and grain average specific gravity known for the soil in the box the void ratio, dry density and degree of saturation could be calculated.

Two boxes of identical dimensions (1.22m x 1.22m x 20.3cm) were built for making two beds of soil simultaneously. Slight variation resulted in the density of the soil beds prepared. The boxes were lined with polyethylene plastic sheets to prevent loss of soil moisture.

The above techniques were employed in making the soil beds at 10% degree of saturation. After measurements had been made on them, the degree of saturation of the soil was brought up to 50% by introducing water from the surface in

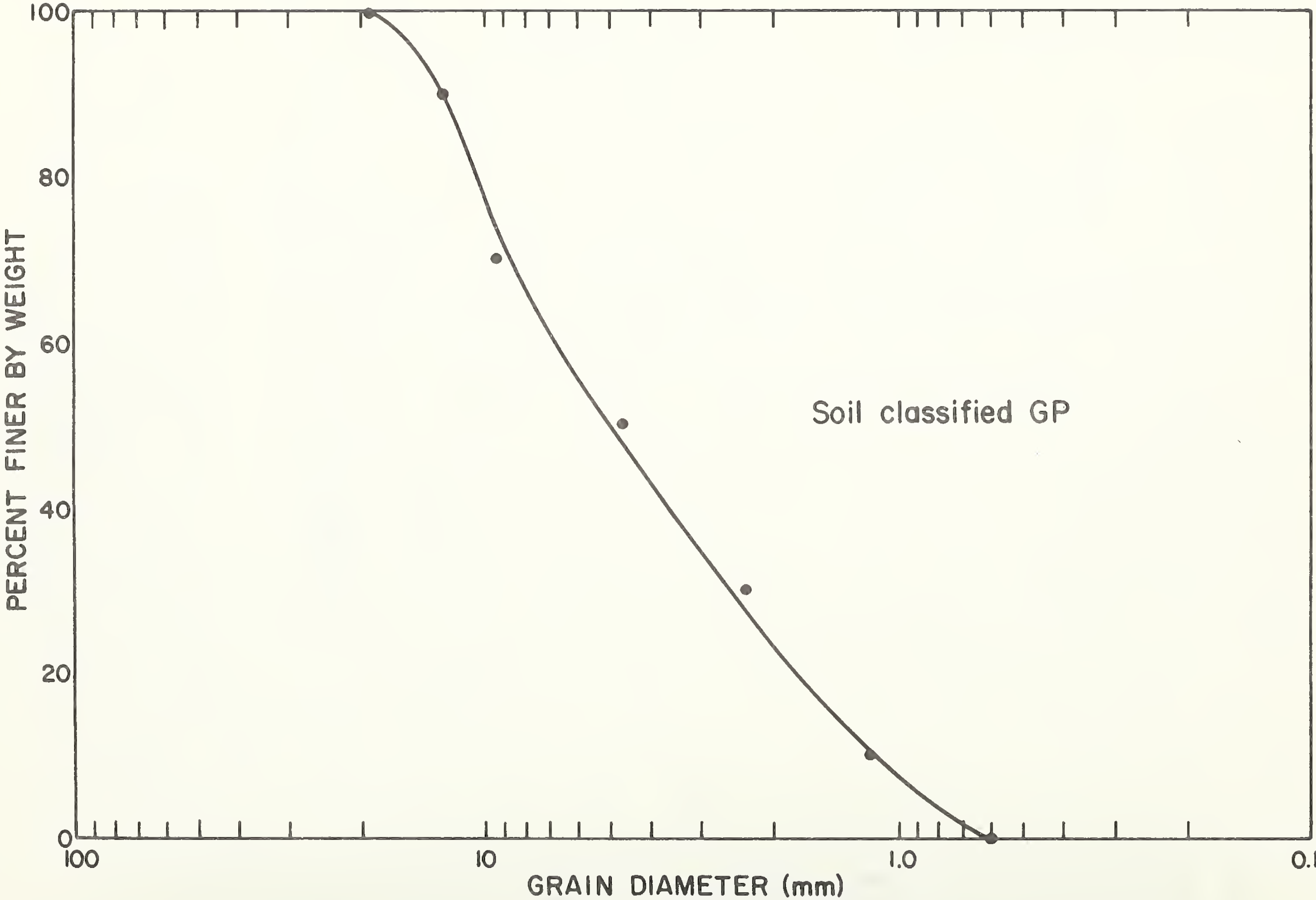

Figure 3. Grain size distribution of gravel samples

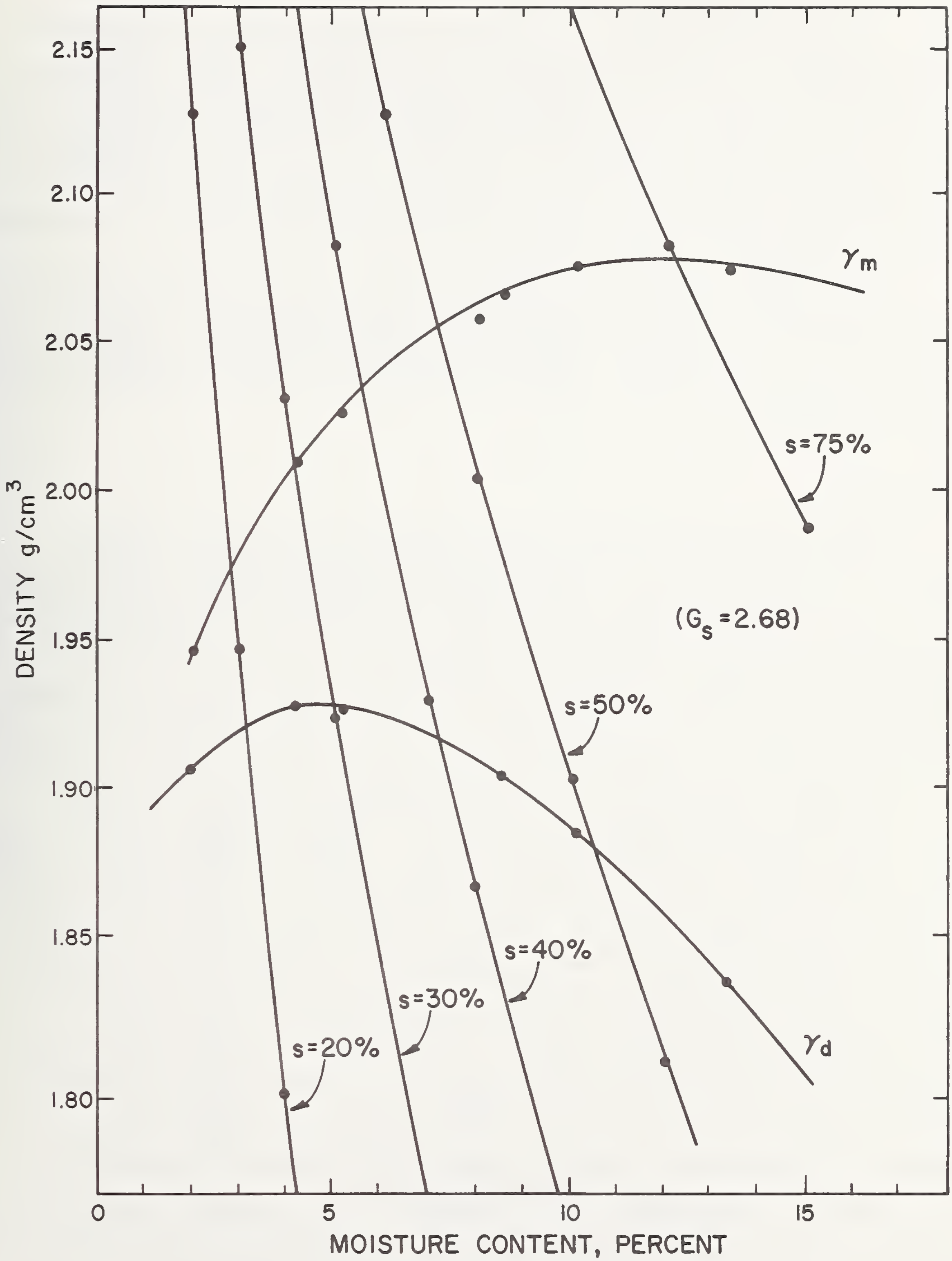

Figure 4. Modified Proctor moisture and density curves of gravel

an amount calculated from the dry density of the prepared soil. The box was again weighed to provide data for accurate determination of the new degree of saturation. Thus compacted dry density of the soil stayed constant from one degree of saturation of the test specimen to another. The same technique was also used to bring saturation to 90%, although the presence of trapped air in the soil presented some difficulties in achieving this high degree of saturation.

Data on the two soil beds at each of the three degrees of saturations are given in table I . Target values for saturation were 10%, 50%, and 90%. Table I gives the actual values obtained for each sample.

3.2 Clay

Some difficulties were encountered in locating a soil with a CL classification because of the large quantities required. Finally, a soil was selected which was dried, crushed, and sieved, retaining the minus number 50 sieve portion. The grain-size distribution curve is shown in figure 5, which also gives its Atterberg limits. It classifies as CL in the Unified Soil Classification System. Compaction characteristics are shown in figure 6.

Dry soil was mixed with an appropriate amount of water in a soil mixer in batches of 110 kg. It was found that the best way to mix soil and water was to add water as a fine mist while the soil was being stirred. After placing the soil in the box, it was compacted with a hand compactor to achieve the desired density and, therefore, the required degree of saturation. After measurements were taken of this soil bed, the soil was remixed with additional water to bring it up to the moisture content necessary to achieve 50% saturation. This time, however, a gasoline-powered, rammer-type compaction machine was used to attain the higher density. For the 90% saturation, the soil bed with 50% saturation was percolated with water

Table I. Properties of Compacted Soils

		Moisture Content (percent)	Dry Density (g/cm^3)	Degree of Saturation (percent)
Gravel	Bed 1	2.0	1.802	11.4
		8.6	1.802	48.9
		15.1	1.802	85.9
	Bed 2	2.0	1.874	12.8
		7.4	1.874	47.3
		12.7	1.874	81.2
Clay		3.5	1.352	9.6
		11.0	1.528	39.3
		23.2	1.528	82.8

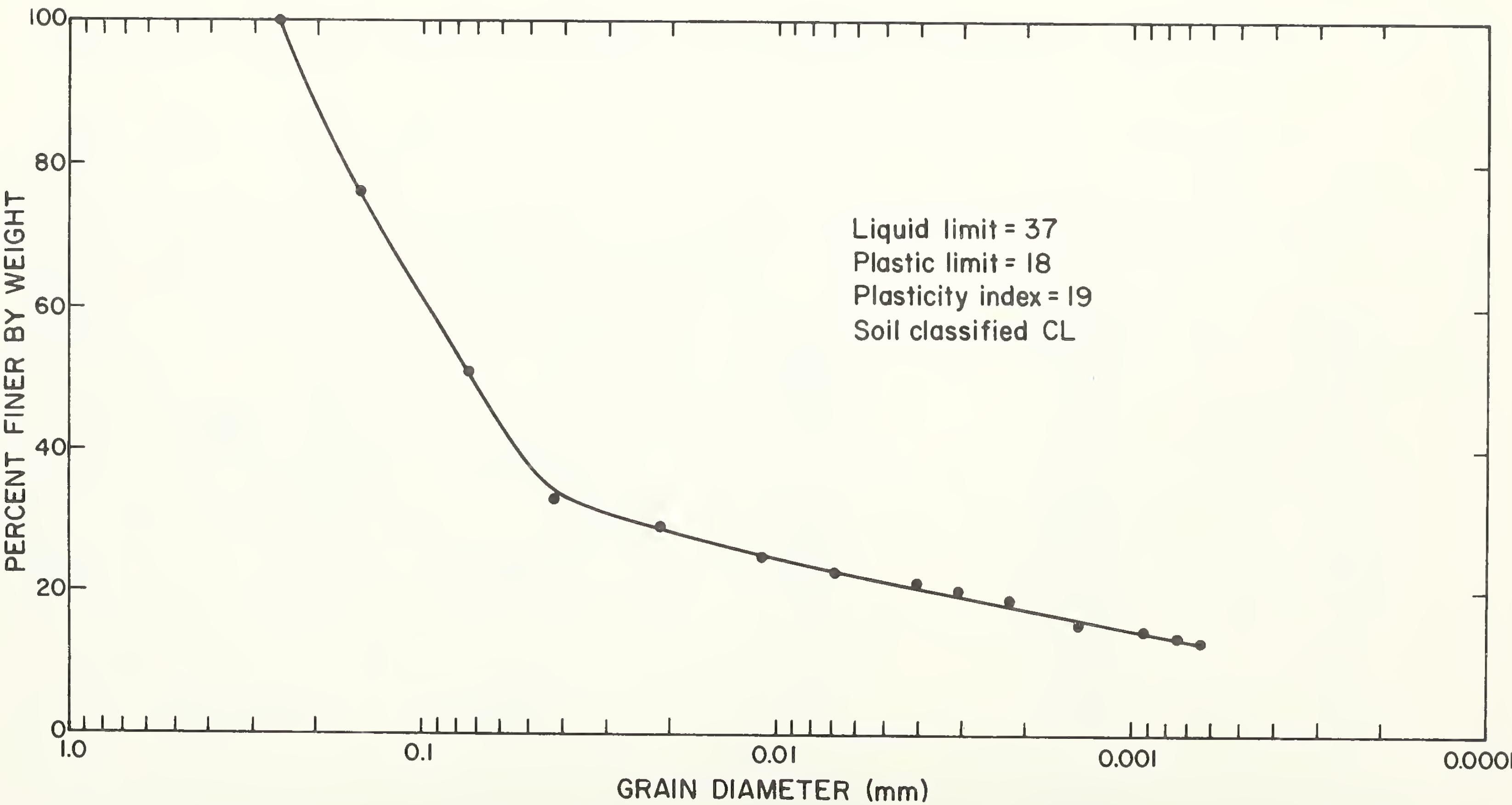

Figure 5. Grain size distribution of clay samples

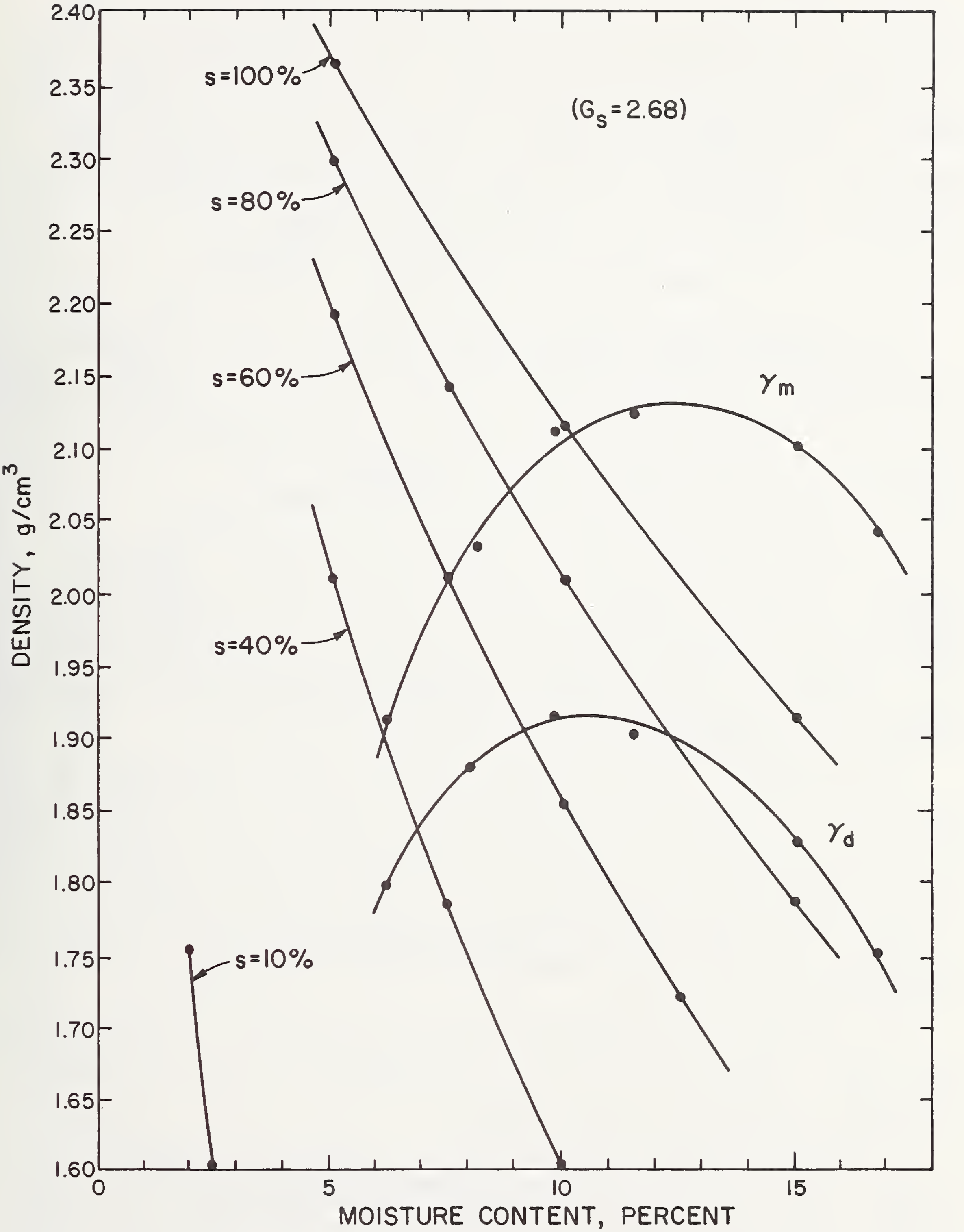

Figure 6. Modified Proctor moisture and density curves of clay

through four plumbing fittings on the bottom of the box. This process of increasing the saturation, was aimed at maintaining a reasonable compaction of the soil, (that of the 50% saturated sample), and avoiding the need to compact a clay soil at 90% saturation, took about four days to accomplish and worked satisfactorily. Data for the clay beds are shown in table I.

4. EXPERIMENTAL RESULTS AND DISCUSSION

Preliminary experiments showed that by sealing the sample in polyethylene not only was the total moisture content retained, but it was retained in a fairly uniform state. A measure of the uniformity was obtained by comparing surface dielectric constant data with the dielectric constant for the layer.

The surface area of all samples was 1.22m x 1.22m. The thickness was intially 20.3 cm; however, that was reduced for samples of higher moisture content in order to facilitate measurements under these conditions of higher microwave absorption.

A sample of the measured data obtained from these experiments is shown in figure 7.

Skin depths derived from all measured data are tabulated in table II, in which sample thicknesses, measured relative dielectric constants, and relevant frequency ranges are also tabulated. The ranges of skin depth includes all values obtained within the corresponding tabulated bandwidth. Single values of relative dielectric constant were obtained for all frequencies within the bandwidth through (11).

A rigorous error analysis for the measurement system has not been done. Sources of errors are discussed here in relation to the effect produced in skin depth.

The measurements were made with a commercial microwave network analyzer, which has an accuracy of ±0.5 dB. The uncertainty in measuring amplitude with this analyzer would therefore produce the greatest skin depth uncertainty at lower frequencies and saturation values because smaller values of attenuation are involved.

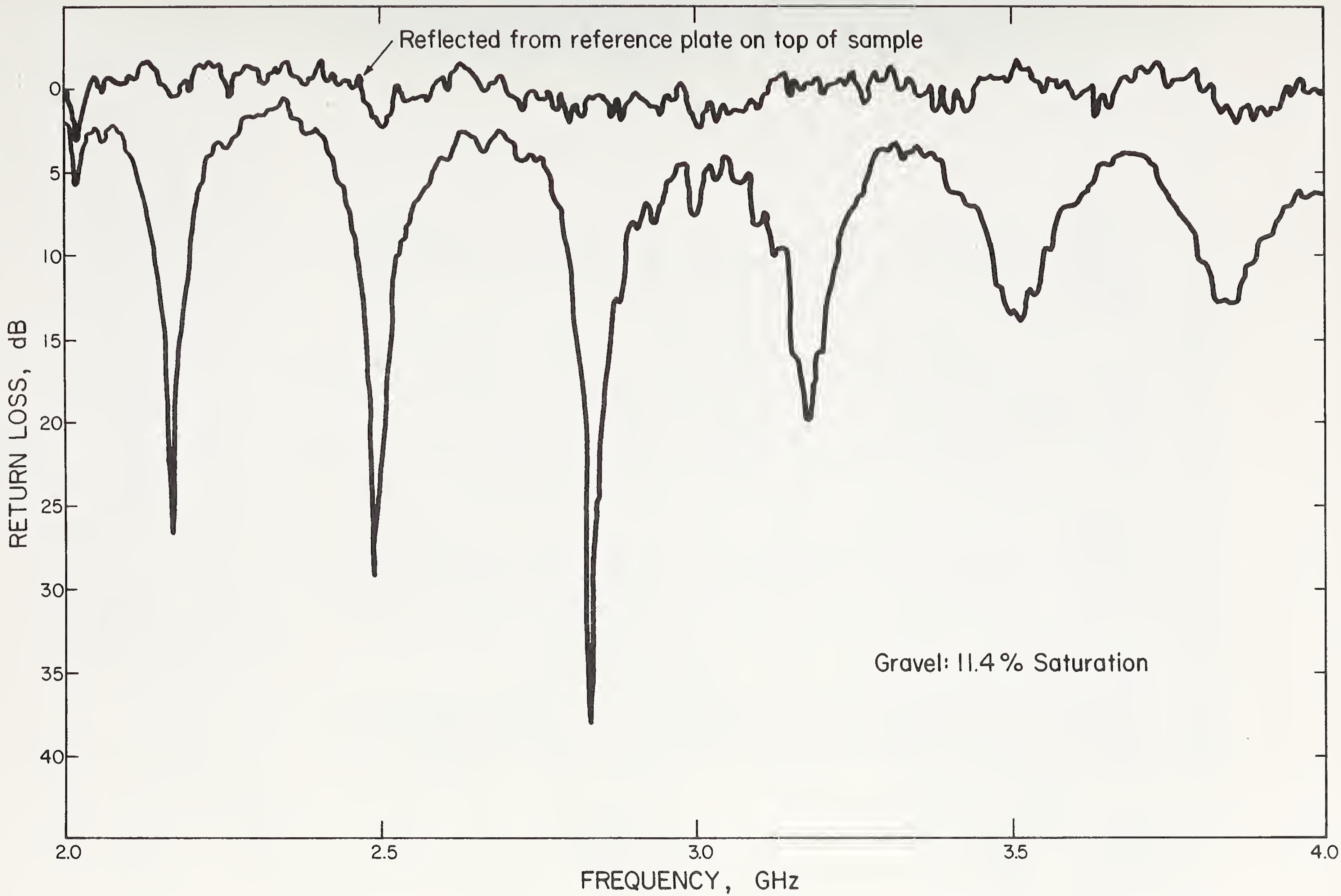

Figure 7. Samples of measured data

Table II. Skin Depths

Material	Saturation (percent)	Sample Thickness (cm)	Frequency (GHz)	Relative Dielectric constant	Skin Depth (cm)
Clay	9.6	20.2	0.5 - 1.0	4.0	30 - 42
	9.6	20.2	2.3 - 2.6	5.1	13 - 19
	9.6	10.8	4.3 - 4.5	4.8	7 - 15
	39.3	8.9	0.5 - 1.0	9.2	10 - 20
	39.3	8.9	2.3 - 2.6	7.7	6 - 18
	39.3	8.9	4.0 - 4.5	7.5	6 - 9
	82.8	2.5	0.6 - 1.7	26.2	5 - 20
	82.8	2.5	2.0 - 3.0	22.1	3 - 6
	82.8	2.5	3.0 - 4.5	20.8	1.5 - 3.5
Gravel	11.4	20.2	0.5 - 1.0	4.9	160 - 315
	11.4	20.2	2.2 - 2.5	4.9	60 - 80
	11.4	20.2	4.0 - 4.5	4.6	17 - 30
	48.9	20.2	0.5 - 1.0	11.2	30 - 200
	48.9	12.1	2.2 - 2.5	13.3	15 - 35
	48.9	7.6	4.0 - 4.5	14.7	4 - 8.5
	85.9	20.2	0.5 - 1.0	15.2	40 - 60
	85.9	20.2	2.2 - 2.5	15.5	5 - 9
	85.9	9.7	4.0 - 4.5	- -	- - - - -

Single ray theory was assumed in these measurements. The sample was placed in the Fresnel diffraction zone of the antennas. Departure from ray theory would increase the uncertainty in skin depth, particularly for samples of lower moisture content. As the moisture content increases, the dielectric constant increases, which produces a focusing of the beam. The net effect is to produce a physical configuration that improves the use of the ray theory assumption. These errors can reasonably be as large as 1 to 2 dB.

Mismatch between antennas and the measuring system could produce a systematic error. This error was minimized by using low VSWR antennas.

An overall error of 1 dB corresponds to a fractional uncertainty of 10% in the skin depth; and error of 2 dB corresponds to a 50% fractional error.

The errors discussed here show that improvement in measurement techniques and hardware could provide more accurate measures of skin depth. In addition, more data of the type provided in the report are required for baseline data purposes. For example, samples having other moisture contents should be prepared for evaluation. Measurements should be made in in-situ situations to detect phenomena that may not be produced in laboratory tests. Other materials, including concrete and asphalt, should be studied to determine the feasibility of using microwave techniques to evaluate surface layers.

5. CONCLUSIONS

The objective of this effort was to investigate relationships that exist between microwave penetration, soil type, moisture content, and microwave frequency. Measurements were made on samples of approximately 10%, 50%, and 90% saturation, at frequencies in the 0.5 - 4.5 GHz range.

Each sample was sealed in polyethylene. This retained the total moisture in the sample and maintained a uniform moisture distribution during the measurement process.

State-of-the-art microwave equipment can readily detect signals of amplitude -80 dBm. Assuming a radiated power of +10 dBm, a microwave system should penetrate a five-skin-depth layer of material (remembering that in the field applications of analyzing pavement systems, the signal would travel through the material twice for a total propagation length of ten skin depths).

Assuming total reflection at the subsurface interface, as is the case with an aluminum baseplate, a 0.5 GHz microwave signal should penetrate a 150-cm layer of approximately 10% saturated clay, or a 25-cm layer of approximately 90% saturated clay. A 4.5-GHz signal should penetrate a 35-cm layer of approximately 10% saturated clay or a 1-cm layer of approximately 90% saturated clay.

In general, gravel exhibited greater skin depths than clay; thus thicker layers of gravel should be penetrated. A 0.5-GHz signal should penetrate 800 cm of approximately 10% saturated gravel, or 120 cm of approximately 90% gravel.

Penetration depths given here should be realized in a field application if the surface reflection can be removed, or at least minimized during the measurement process. Possible techniques for controlling the adverse effect of the surface reflection include: providing an auxiliary circuit to cancel the surface reflection, or making the measurement in the time domain and eliminating the surface reflection with proper gating circuitry.

Penetration depths given here are based on a total reflection at the lower boundary of medium 2. Total reflection was accomplished in these experiments because aluminum was used as the base material. In a pavement system consisting of a layer of gravel over clay, the penetration capability of the system would be reduced because total reflection at the gravel-clay interface does not occur. A portion of the signal would penetrate the clay. The degree of degradation is dependent upon the moisture contents of both materials. A layer of 10% saturated gravel over 10% saturated clay would reduce the penetration depth of the gravel to approximately three skin depths, or 300 cm at 0.5 GHz. If the saturations are increased to 90% for both, the penetration depth of the gravel is approximately 120 cm. These numerical values are based on the assumption that surface reflection does not limit the measurement range capability of the system.

6. ACKNOWLEDGEMENTS

The author is indebted to Professors Hon-Yim Ko and Edward Sampson, Jr., Department of Civil and Environmental Engineering, University of Colorado, for preparing the soil samples.

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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.)

The objective of this work was to establish the feasibility of using active microwave techniques to differentiate between the different subsurface layers in a pavement system. The electromagnetic attenuation properties of clay and gravel soils were measured as a function of moisture content and frequency. Measurements were done at frequencies in the 0.5 - 4.5 GHz range. Soil samples were compounded in the laboratory at approximately 10, 50 and 90% saturation. Sample thickness was in the range 2.5 - 20.3 cm. Each homogeneous sample was sealed in a polyethylene container to retain the total moisture and to maintain a constant moisture content with depth.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Attenuation; clay; gravel; measurements; microwave; skin depth.

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