Technical Report RSC-23

LABORATORY MEASUREMENT OF THE COMPLEX DIELECTRIC CONSTANT OF SOILS

by

M. L. WIEBE

October 1971

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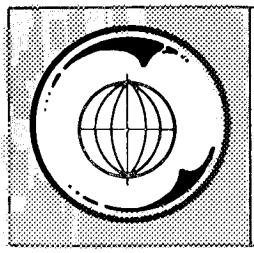

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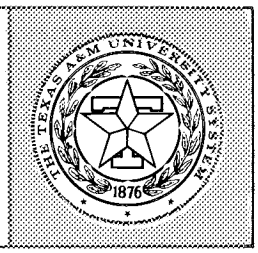

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INTRODUCTION

The dielectric constant of a material is an extremely important parameter when considering passive radiometric remote sensing applications. This is because the emitted energy measured by a microwave radiometer is dependent on the dielectric constant of the surface being scanned (Jean, 1970). Two techniques of measuring dielectric constants are described in this paper and the results are compared with those of other experimenters. The first method involves a dielectric located in air (Hertel, Straiton, and Tolbert, 1953). The second method uses basically the same theoretical approach, but the dielectric under consideration is located inside a section of waveguide, similar to the technique proposed by Rouse and Giarola (1970).

RELATION OF COMPLEX PERMITTIVITY TO PROPAGATION CONSTANT

The two techniques for measurement of complex permittivity are based on the relationship between the propagation constant of a material, and the complex permittivity of the material (Hertel, et al., 1953).

The propagation constant of a medium is defined by

$$\gamma \equiv \alpha + j\beta$$

where: α is the attenuation constant in nepers/meter

β is the phase constant in radians/meter

Also

$$\gamma = j\omega\sqrt{\mu\varepsilon_c}$$

where: w is the angular frequency of the wave

μ is the permeability of the medium

ε_c is the complex permittivity of the medium

and

$$\varepsilon_c \equiv \varepsilon' - j\varepsilon''$$

Substituting,

$$\alpha + j\beta = j\omega\sqrt{\mu(\varepsilon' - j\varepsilon'')}$$

By equating the real and the imaginary parts of both sides, the real and imaginary parts of the permittivity may be expressed as

$$\varepsilon' = \frac{\beta^2 - \alpha^2}{\omega^2 \mu}$$

and

$$\varepsilon'' = \frac{2\alpha\beta}{\omega^2 \mu}$$

Or in terms of the relative dielectric constant

$$k' \equiv \frac{\varepsilon'}{\varepsilon_0} = \frac{\beta^2 - \alpha^2}{\omega^2 \mu \varepsilon_0}$$

$$k'' \equiv \frac{\varepsilon''}{\varepsilon_0} = \frac{2\alpha\beta}{\omega^2 \mu \varepsilon_0}$$

For materials such that $\mu = \mu_0$ these may be written as

$$k' = \frac{\beta^2 - \alpha^2}{\beta_0^2}$$

$$k'' = \frac{2\alpha\beta}{\beta_0^2}$$

where: β_0 is the phase constant of free-space

$$\beta_0 = \omega\sqrt{\mu_0 \varepsilon_0}$$

The relationship between the propagation constant and the complex permittivity is slightly different if the dielectric is located inside a waveguide because of the cutoff properties of the guide (Ramo, Whinnery, Van Duzer, 1965).

Inside a waveguide

$$\gamma = \sqrt{K_c^2 - K^2}$$

where: K is the wave number

K_c is the wave number evaluated at the guide cut-off frequency

Or $$K_c = \frac{2\pi}{\lambda_c}$$

where: λ_c is the cutoff wavelength

and $$K = \omega\sqrt{\mu(\varepsilon' - j\varepsilon'')}$$

Substituting as before

$$\alpha + j\beta = \sqrt{K_c^2 - \omega^2[\mu(\varepsilon' - j\varepsilon'')]}$$

Solving for ε' and ε''

$$\varepsilon' = \frac{\beta^2 - \alpha^2 + K_c^2}{\omega^2\mu}$$

$$\varepsilon'' = \frac{2\alpha\beta}{\omega^2\mu}$$

Or, as shown previously,

$$k' = \frac{\beta^2 - \alpha^2 + K_c^2}{\beta_0^2}$$

$$k'' = \frac{2\alpha\beta}{\beta_0^2}$$

Thus the real and imaginary parts of the dielectric constant may be expressed directly as functions of the phase

and attenuation constants of the material and the wavelength of measurement.

MEASUREMENT OF PHASE AND ATTENUATION CONSTANTS

The experimental apparatus for measuring the propagation constant is shown in Figure 1 for the free space method. For the guide method, the same equipment is used but the horn antennas are replaced with a section of waveguide and the guide sample holder (see Appendix A).

For measurement of the phase constant, the modulated signal is divided between the sample holder and the calibrated phase shifter. The signals are coupled back together, and a minimum is observed on the indicator when they are 180° out of phase. The phase shifter is adjusted for this minimum both with the holder empty and again with the sample in place. The difference in phase readings is the phase shift introduced by the sample dielectric. The procedure is repeated for several sample lengths and the results plotted as phase shift vs. sample length, as in Figure 2. The slope of the resulting line is the measured phase constant.

This measured value is the difference between the free space (or empty guide) phase constant and the phase

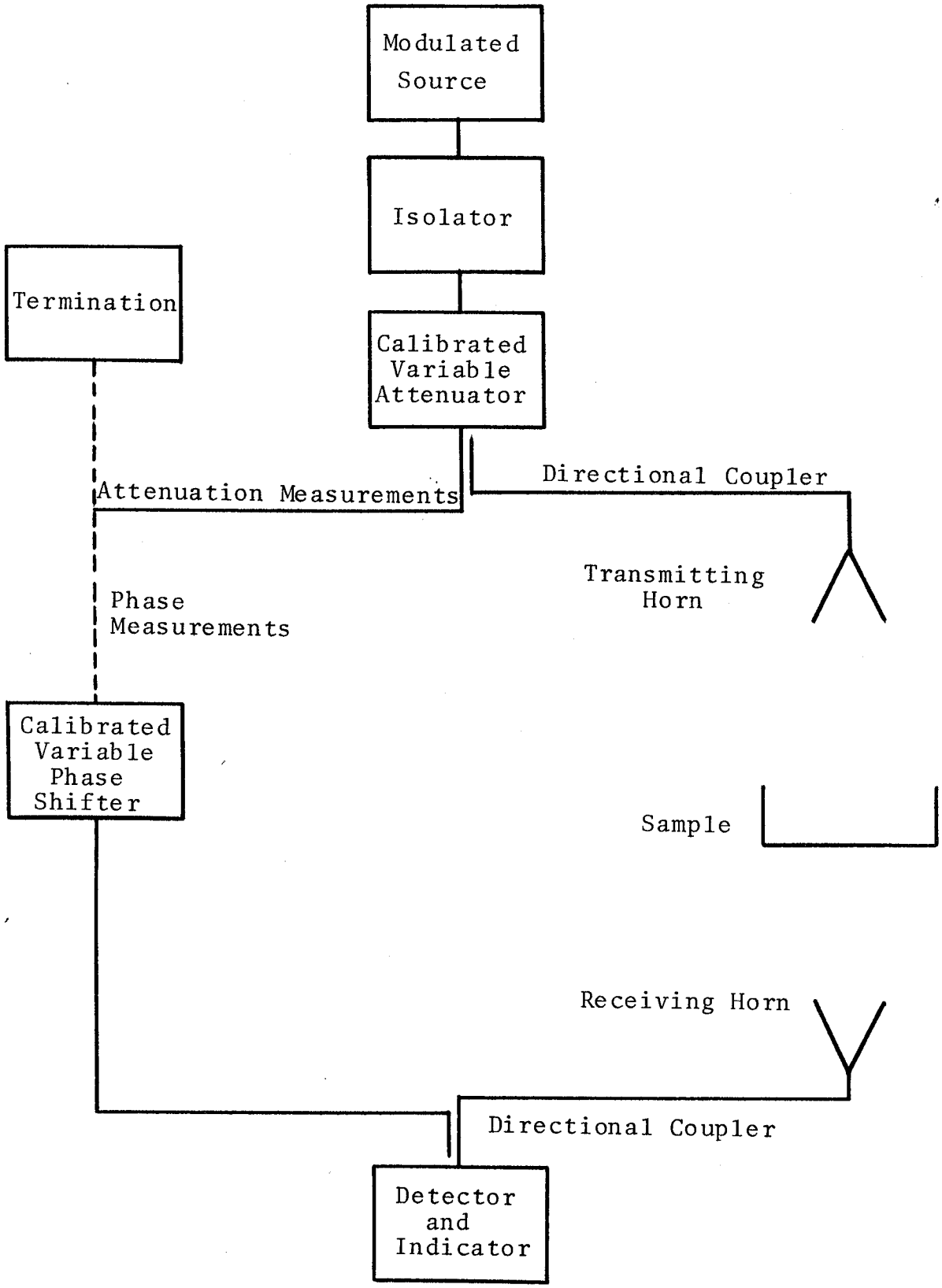


Figure 1. Apparatus for Free Space Measurement of Complex Dielectric Constant

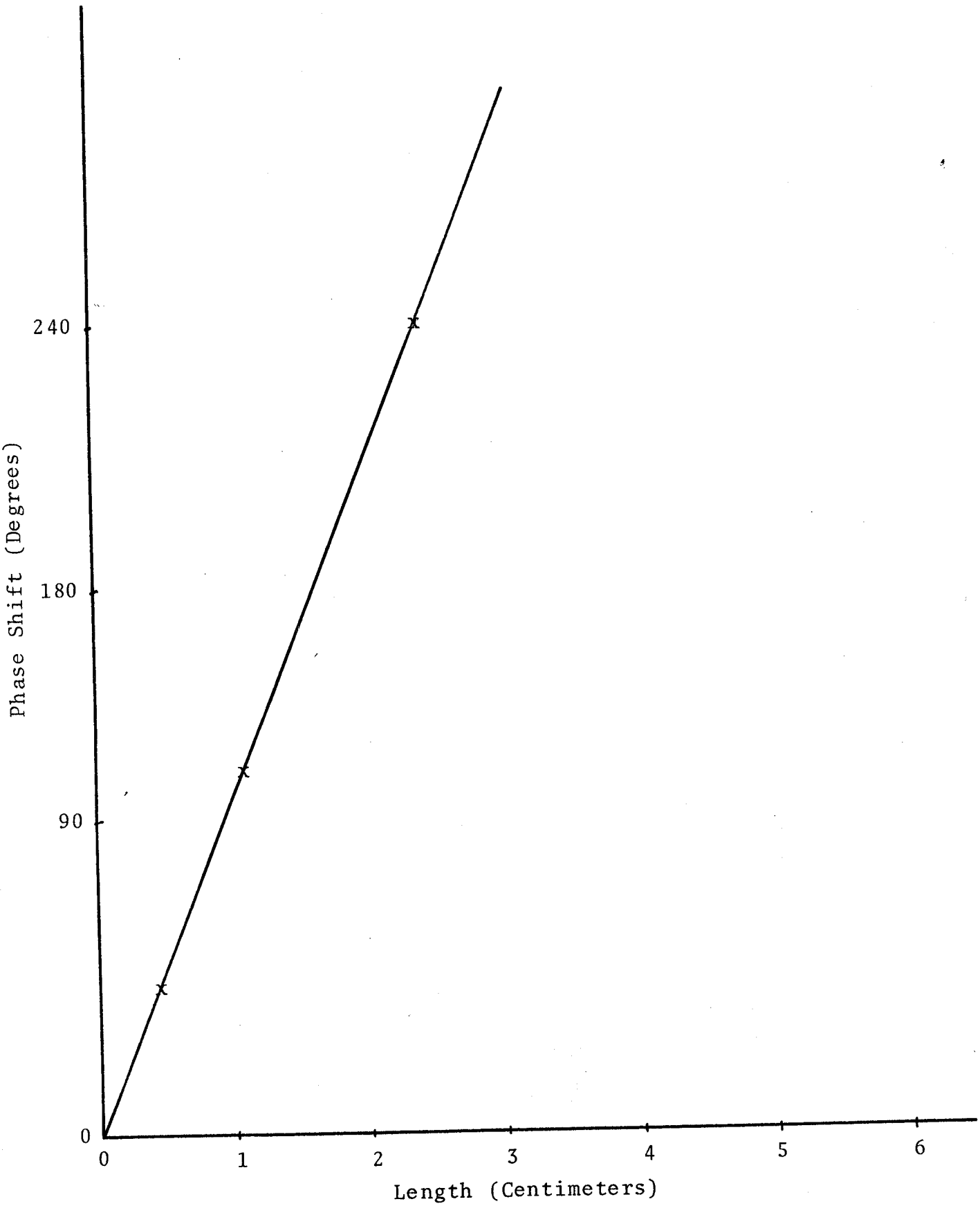


Figure 2. Determination of Phase Constant

constant of the material.

$$\frac{\Delta \theta}{\Delta \ell} = \beta - \beta_o$$

where: $\Delta\theta/\Delta\ell$ is the slope of the line described above

β is the actual phase constant of the sample dielectric

β_0 is the phase constant of free space or of the empty guide, depending on the method used

For the free space method

$$\beta_o = \frac{2\pi}{\lambda_o}$$

For the guide method

$$\beta_o = \frac{2\pi}{\lambda_g}$$

where: λ_0 is the free space wavelength

λ_g is the wavelength in the guide

Therefore the actual phase constant of the dielectric is

$$\beta = \frac{\Delta \theta}{\Delta \ell} + \beta_o$$

The attenuation constant is determined by terminating the phase shifter branch as shown in Figure 1. The calibrated attenuator and gain adjustments on the

indicator are adjusted with the empty sample holder in place to give a convenient reference level of the indicator. Then by adjusting the attenuator (but not the indicator gain) to obtain the same reference level for several lengths of sample material, the attenuation introduced by the dielectric may be found from the difference between the empty and loaded readings. The plot of attenuation vs. sample length will in general not be a linear function, except for very lossy materials (Hertel, Straiton, and Tolbert, 1953). This is due to variations in impedance as a function of multiples of half wavelength thicknesses (Purington and Pate, 1967) and is similar to a damped sine wave. The attenuation factor is obtained by plotting a large number of points, and taking the slope of line drawn as the average of the points, as shown in Figure 3. This non-linearity decreases as the sample length increases and the "oscillations" are damped out. For this reason it is advisable to employ samples which are as long as possible, particularly for low loss materials.

For the free space method, the antenna spacing to insure a plane wave at the receiving horn was determined from Kraus (1950) as

$$r \geq \frac{2a^2}{\lambda_o}$$

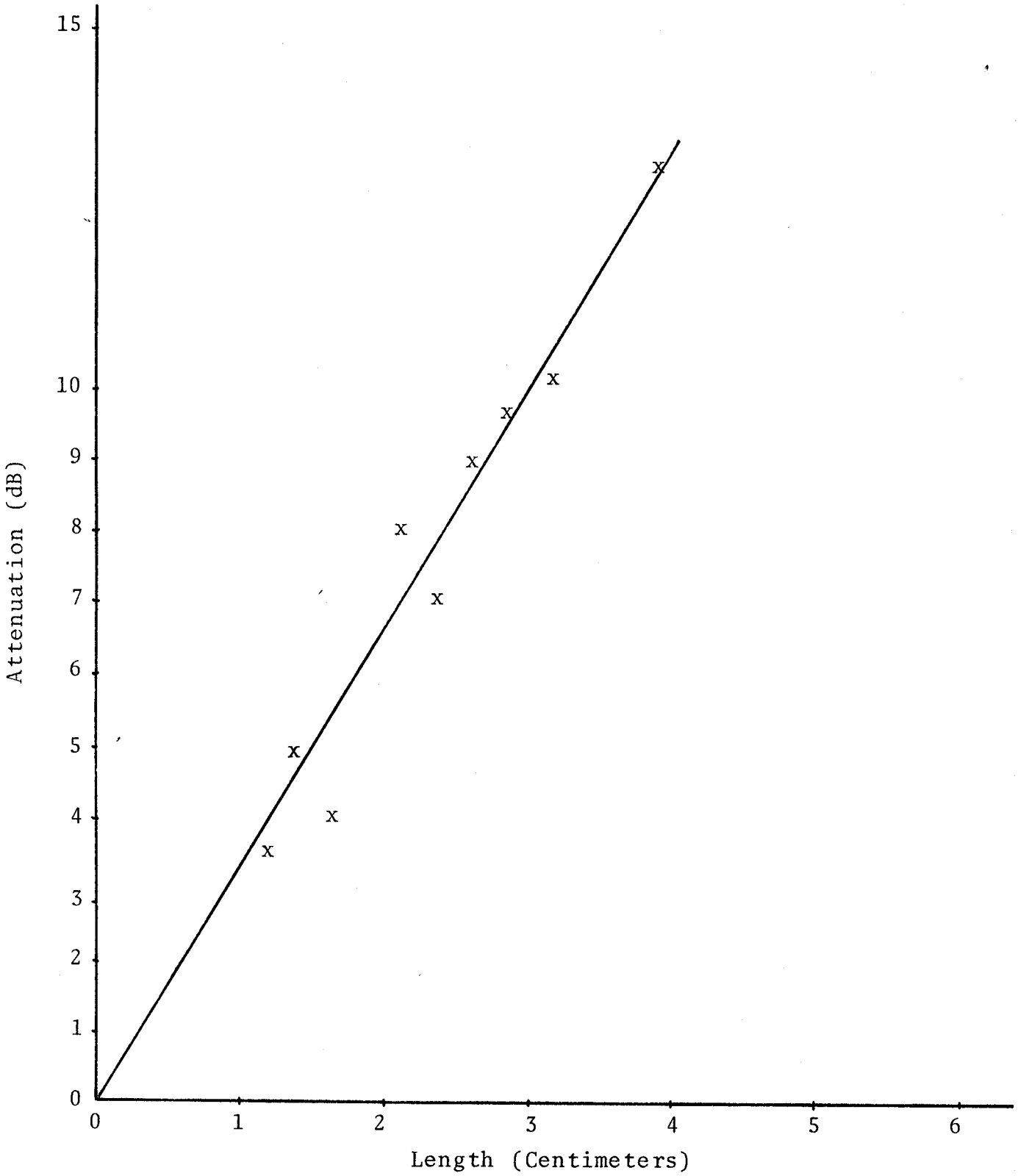


Figure 3. Determination of Attenuation Constant

where: r is the minimum horn separation

a is the receiving horn diameter or width

λ_0 is the free space wavelength

It was also determined experimentally that it is necessary to separate the receiving horn and the sample to minimize the effects of reflections from the receiving antenna itself. To achieve this, the separation between the sample and transmitting horn was maintained at the minimum separation described above and the receiving horn was moved as far as power limitations would permit. The equipment was surrounded by absorber materials to minimize external reflections.

As reported by Straiton and Tolbert (1945) the packing of a material affects the measured dielectric constant, with both real and imaginery parts increasing as compacting force is increased. Therefore, the materials being measured may be packed consistently, as done by Lundien (1971) with known forces, or allowed to pack naturally (i.e., wet soils naturally compact more than dry soils). The latter approach was considered more applicable since it would more likely simulate natural terrain conditions. The free space method is particularly well suited for natural packing.

EXPERIMENTAL RESULTS OF MEASUREMENTS ON MOIST SAND

In order to evaluate the measurement techniques described above, a study was made of the complex dielectric constant of sand as a function of moisture content at 9 GHz. Moisture content was figured on a dry weight basis

$$M = \frac{W_w - W_d}{W_d} \times 100\%$$

where: M is the percent moisture

W_w is the weight of the wet mixture

W_d is the weight of the dried sand

The results of both techniques are shown graphically in Figures 4 and 5. Also shown are the results of Lundien (1971) for 1.499 GHz and Richerson (1971) for 31.4 GHz. Both employed techniques similar to the free space method described above.

Both the guided wave and the free space method yield results which appear to be consistent with the other reported results. The real part is approximately independent of frequency, while the imaginary term, which depends on losses, exhibits considerable variation, increasing with increasing frequency.

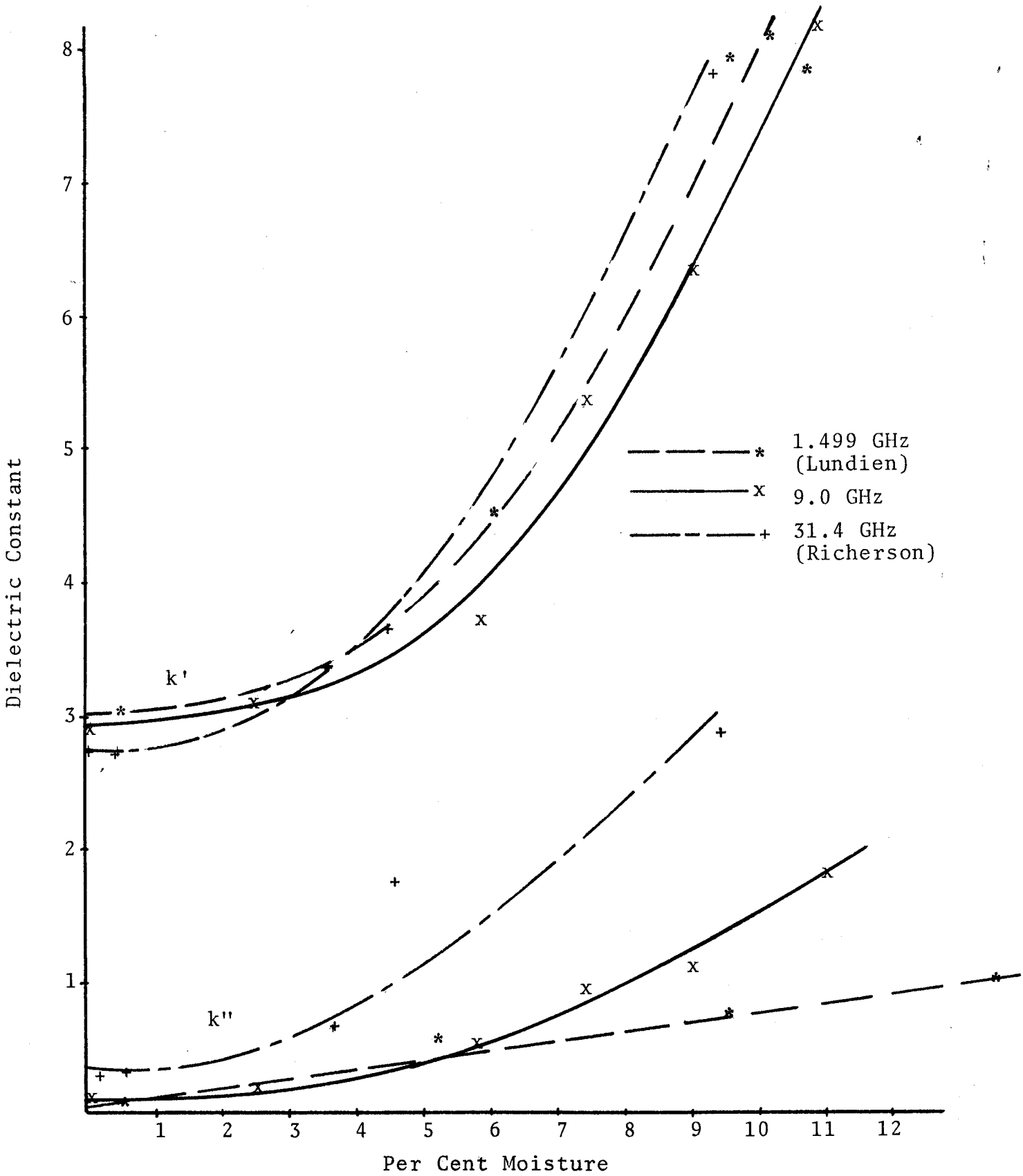


Figure 4. Results of Free Space Method

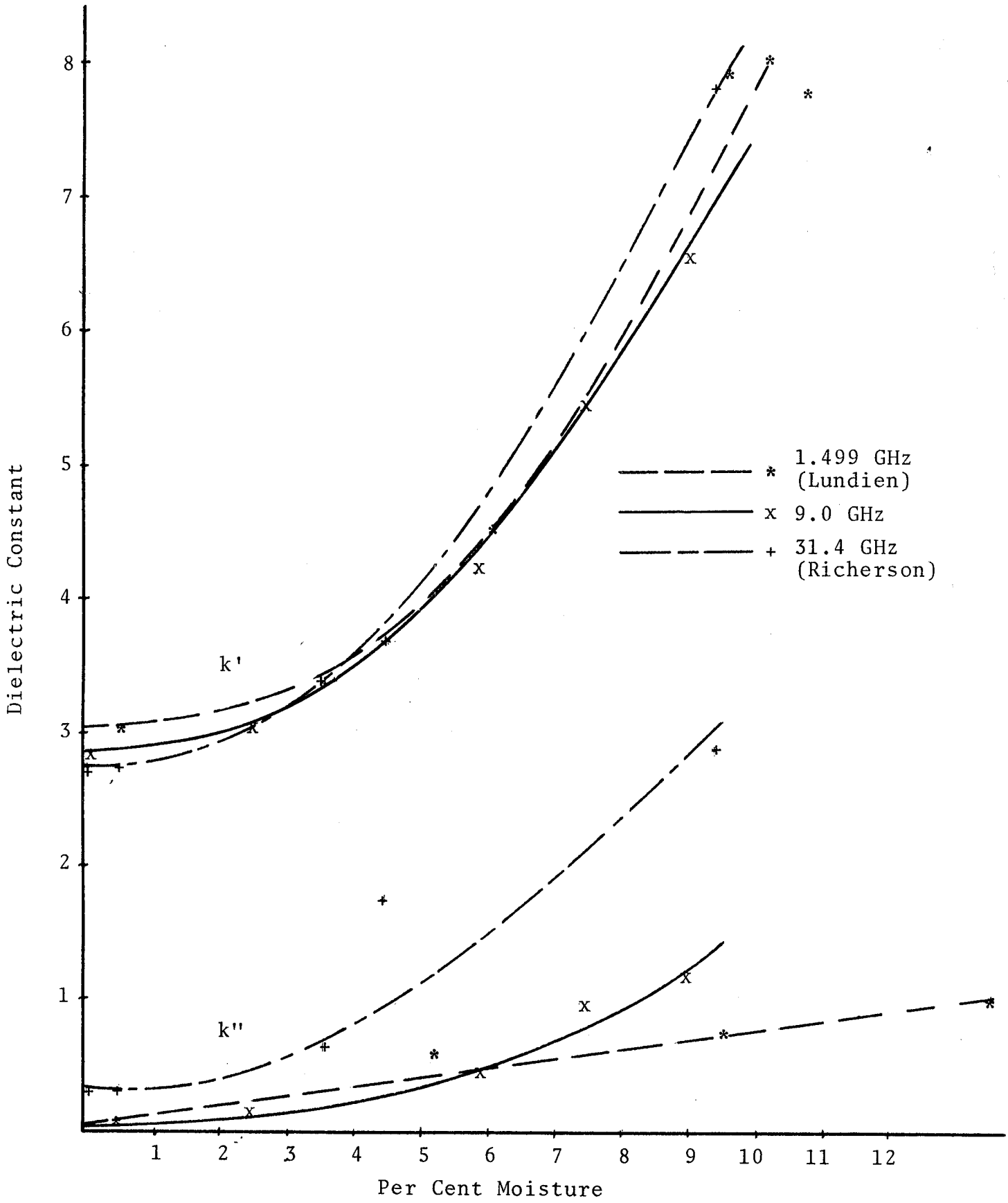


Figure 5. Results of Guide Method

MEASUREMENTS ON TEXAS SOILS

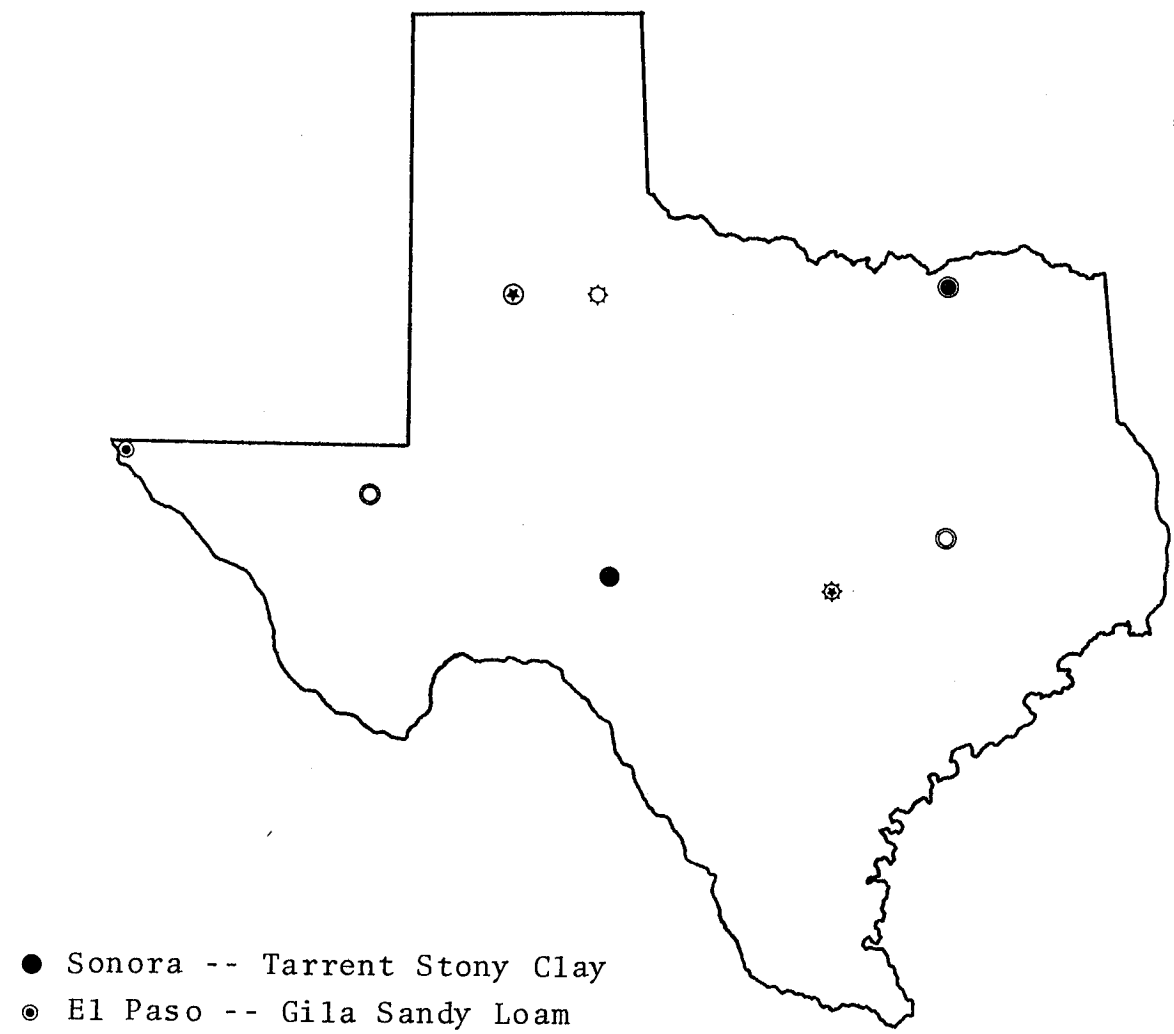
After it had been determined that the measurement techniques were reliable, a study was made on an assortment of Texas soils at a frequency of 10.625 GHz. The soil samples were obtained from several representative regions of the state (Carter, 1931), as shown in Figure 6. The waveguide method was used due to sample size limitations.

The following variables were considered for the various soil types: 1. Moisture Content, 2. Compaction, 3. Curing Time.

As noted above, the dielectric constant is extremely dependent on the moisture content of the soil. Therefore, the moisture was varied from dry soil to near saturation.

In order to further investigate the effects of compaction noted by Straiton and Tolbert (1945) the samples were measured at compactions of 5 and 20 Newtons per square centimeter.

The samples were compacted using a controlled full compacting hammer, as described by Lambe (1951). This device employs a known weight falling through a measured distance to impact a known volume of soil.



- Sonora -- Tarrent Stony Clay
- El Paso -- Gila Sandy Loam
- Pecos -- Hoban Sandy Loam
- Lubbock -- Amarillo Fine Sandy Loam
- Spur -- Abilene Clay Loam
- San Marcos -- Houston Black Clay
- Bonham -- Miller Clay
- Robertson County -- Lake Sand

FIGURE 6. Texas Soil Sample Locations

This results in a specific amount of energy (in Joules, or Newton-Meters) per volume (in cubic meters). This may also be expressed as Newtons per square meter. A computer program was used to calculate the required distance of fall as a function of the length of the sample for the constant cross sectional area of the holder.

As reported by Lundien (1971) and Grim (1968) when water is held in a soil, the water which is in direct contact with the surface of the soil particles (absorbed) has characteristics which are very different from free water. In particular, the water within a few molecules of clay particles may have a relative dielectric constant as small as one-tenth that of free water, probably due to the restricted molecular movement (Grim, 1968). Because a finite amount of time is necessary for absorption to occur, measurements were made for samples immediately after the water was mixed and also after samples were allowed to cure for twenty-four hours in sealed containers.

The results of all those measurements are shown in Figures 7 through 15 for the individual soil types, and in Figures 16 through 19 for all the soils tested.

Inspection of Figure 16 reveals agreement with the observations of Lundien (1971); that is in general the fine, clay-type soils have lower dielectric constants and the sandy soils have the highest dielectric constants. This may be explained by the fact that the finer soils have more particle surface area and thus have more absorbed water and less free water with a resulting lower dielectric constant.

Figures 7 through 15 reveal that time is also a factor, with the relative dielectric constant of all soils tested decreasing with time. This may also be explained in terms of the absorbed water concept. With the passage of time, more water is able to penetrate the soil particles (Lambe and Whitman, 1968) and thus more water is in direct contact with the surface of particles and is in state of the restricted molecular motion as described above. This would also explain the fact that this time effect is more pronounced in finer soils and less obvious in the coarser, sandy soils. Comparison of Figures 16 and 18 also shows that the range of values for all the soils tested increases with time. Thus spreading effect makes the different soil types more obvious and may be explained by the time dependence of absorption.

It may be seen from Figures 7 through 15 that increasing the compaction of the sample increases the dielectric constant. This effect is most obvious in the medium moisture contents, with less effect at higher and lower moisture contents. In the medium moisture range this may be due to the higher compaction forcing air out from between the soil particles, thus removing the component of the soil/water/air mixture which has the lowest dielectric constant and raising the dielectric constnat of the mixture.

The decrease in this effect at higher moisture contents may be due to the face that the voids between soil particles contain mostly water with less air to remove. At lower moisture contents the soil is not well enough lubricated to compress and force the air out (Lambe, 1951).

With the exception of Tarrant Stony Clay, all the soils tested were very homogeneous. The Tarrant Clay, however had several larger pieces of stone, and tests were conducted both with the sample in its natural state and with the larger stones removed by passing through a one-millimeter seive. Comparison of Figures 7 and 8 shows that the seived sample, which of course was finer grained, has lower values for the relative

dielectric constant. Again, this is probably due to the absorbed water concept described above. This difference would indicate that some knowledge of the amount of rock or other debris in a soil would be necessary in a radiometric study of an area.

CONCLUSIONS

As shown by the results of the several samples tested, there is a definite correlation between the relative dielectric constant of a soil and certain physical properties of the soil, particularly the moisture content and, for the finer soils, the curing time. Becuase of the additional dependence on soil texture (i.e. sand, clay, etc.) it is possible that even general knowledge of the soil texture, rather than of the specific type of soil, would aid in the interpretation and application of radiometric data. While moisture content has the most pronounced effect on the relative dielectric constant, the effects of other properties such as compaction and debris content might enable a wider variety of information to be extracted as microwave radiometric techniques are improved and used in conjunction with other types of sensors.

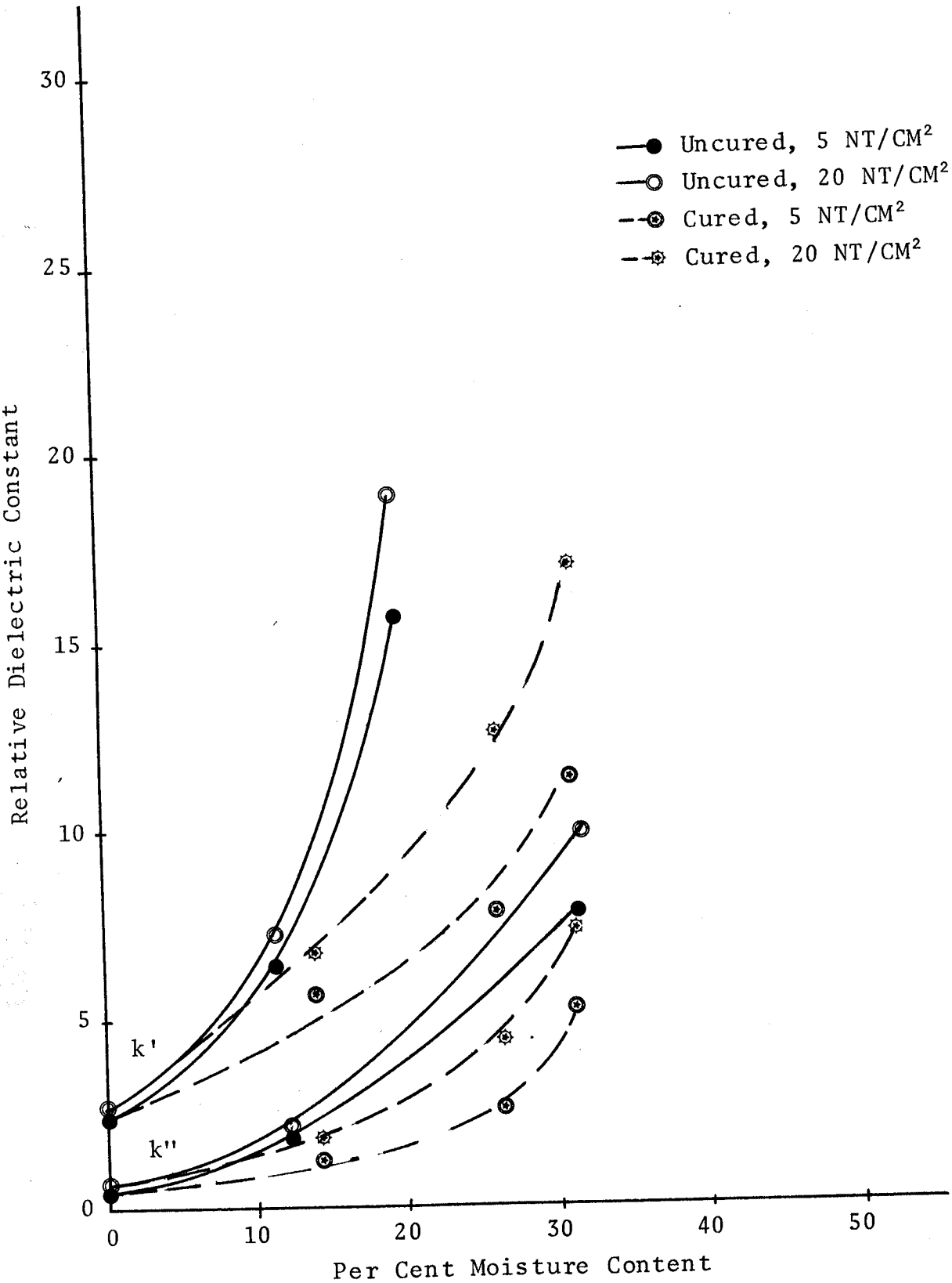


FIGURE 7. Tarrant Stony Clay (Unseived)

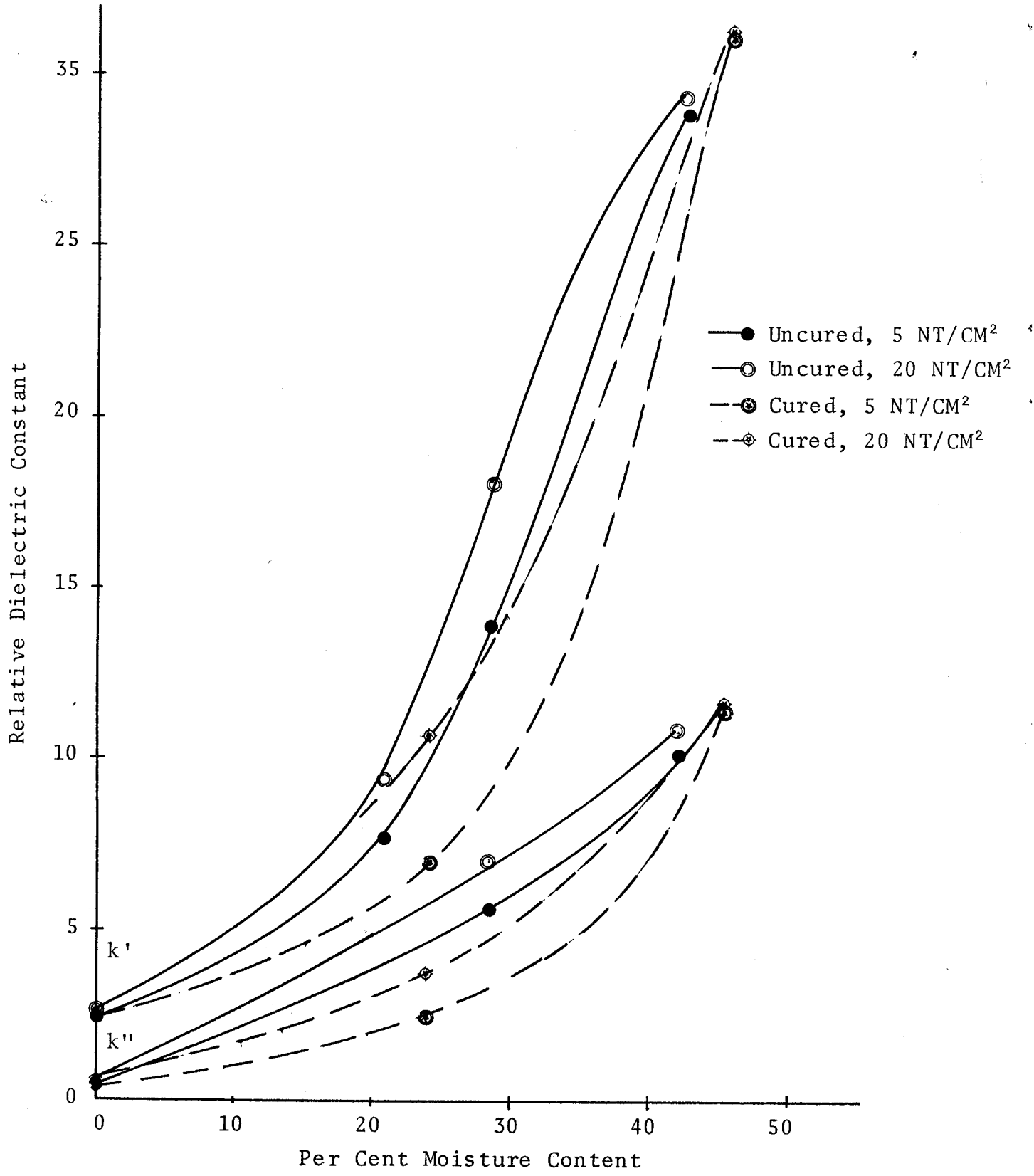


FIGURE 8. Tarrant Stony Clay (Seived)

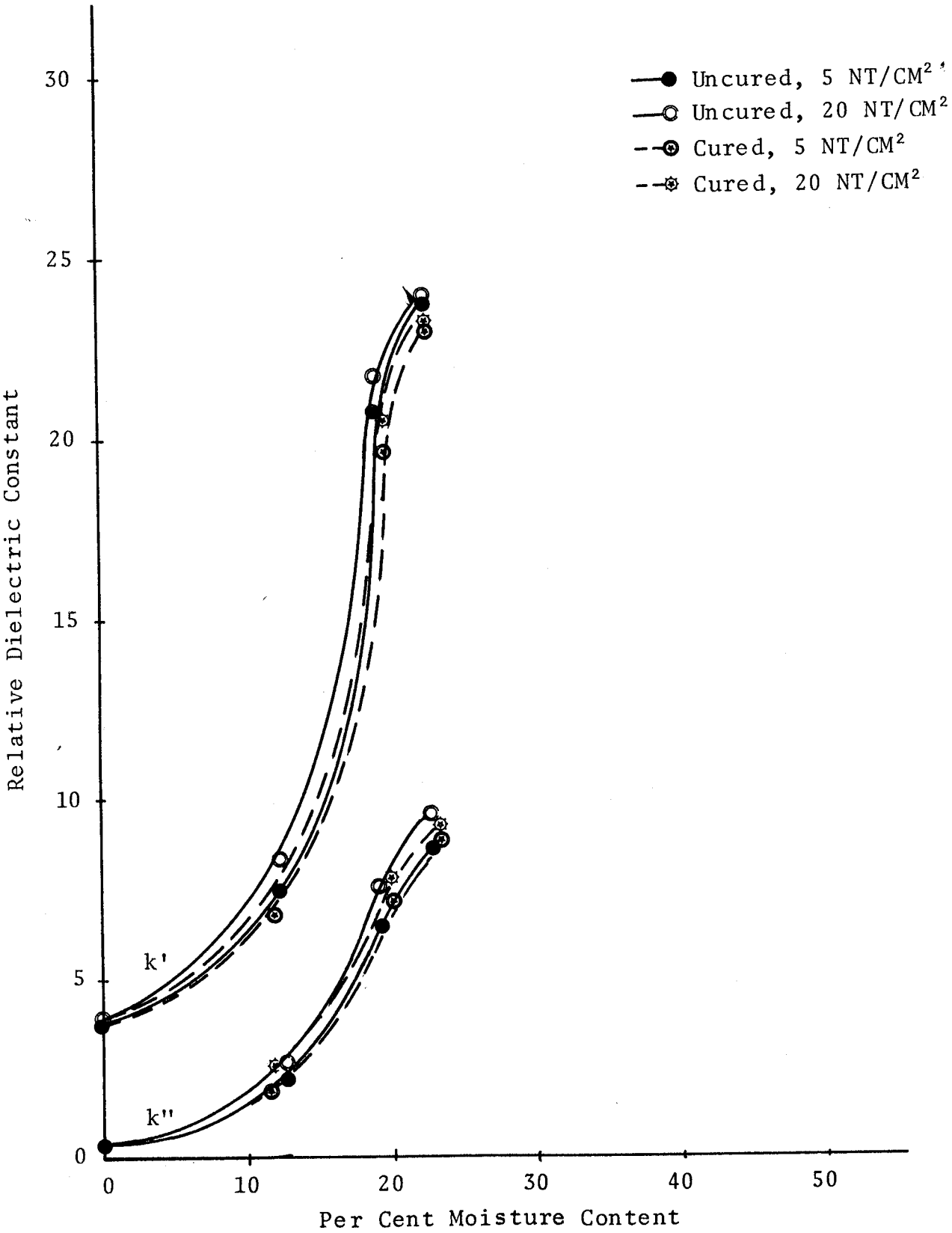


FIGURE 9. Gila Sandy Loam

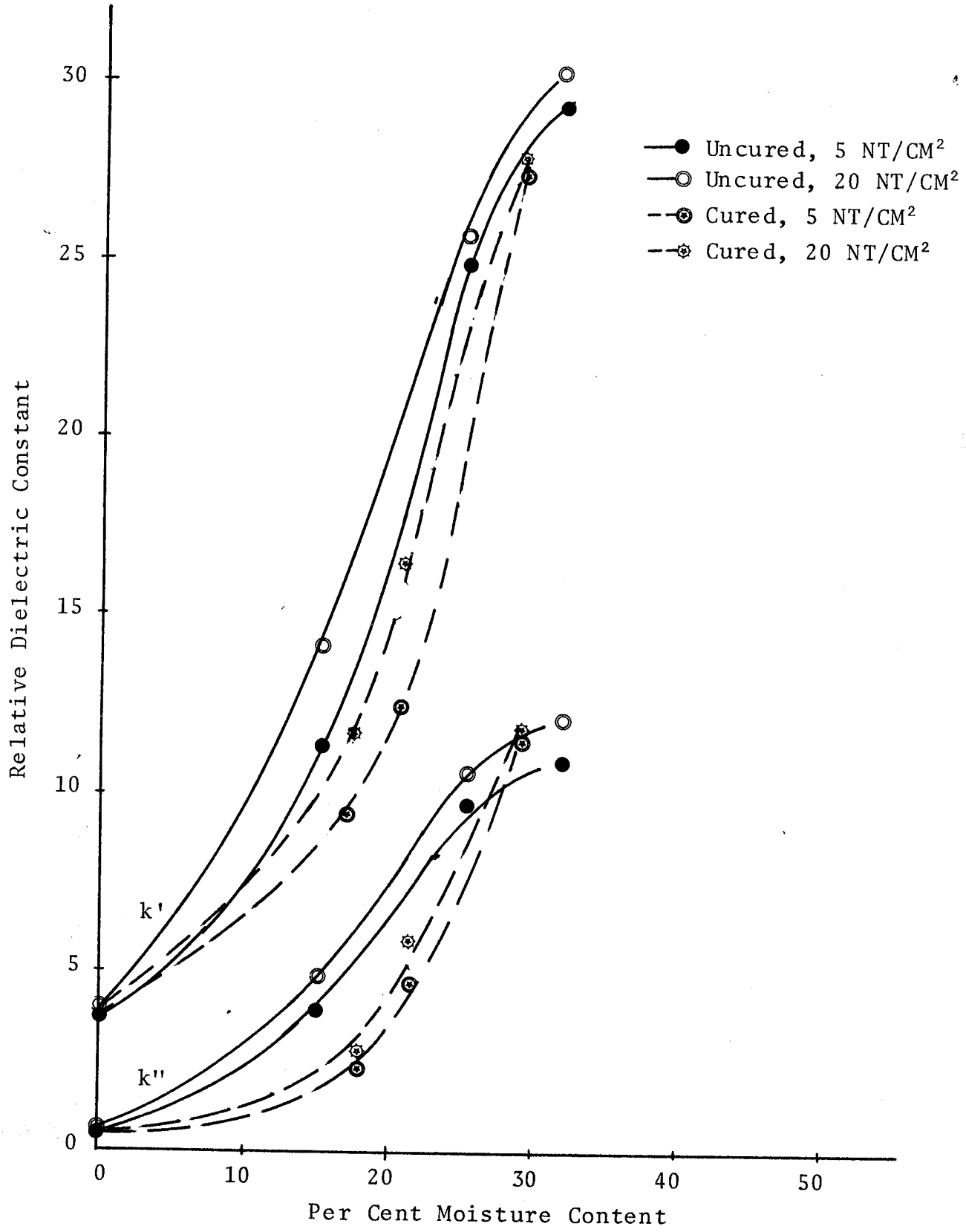


FIGURE 10. Hoban Sandy Loam

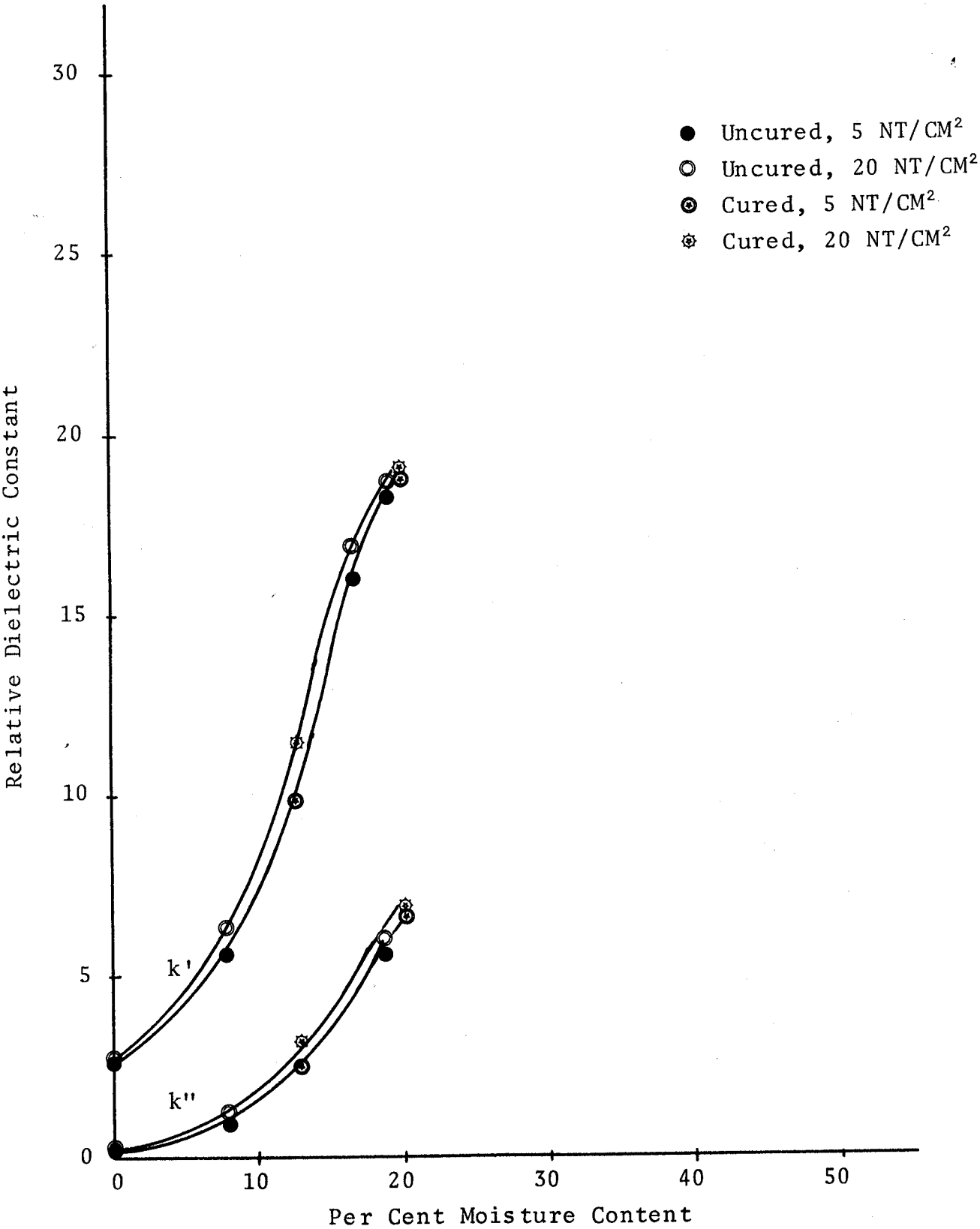


FIGURE 11. Amarillo Fine Sandy Loam

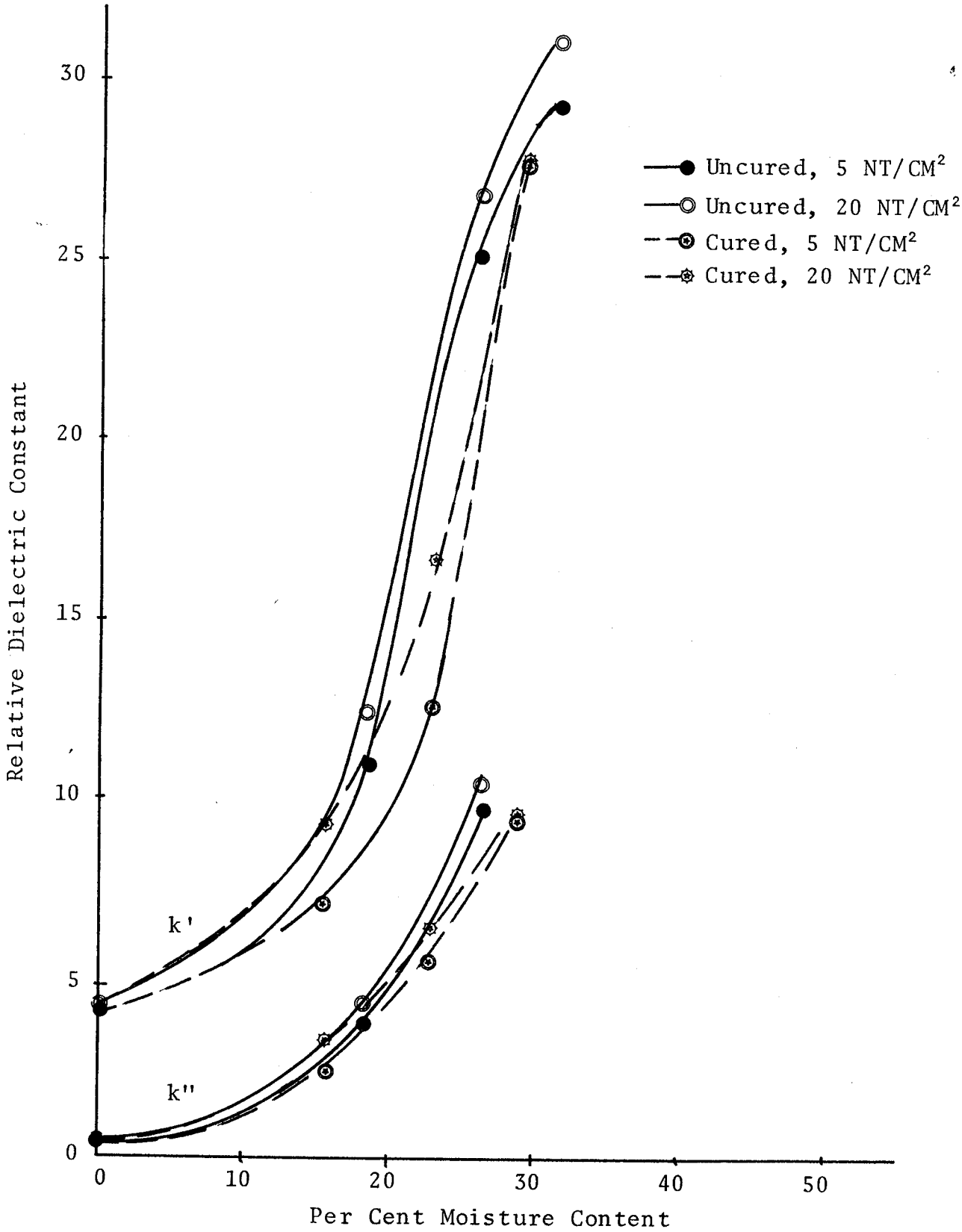


FIGURE 12. Abilene Clay Loam

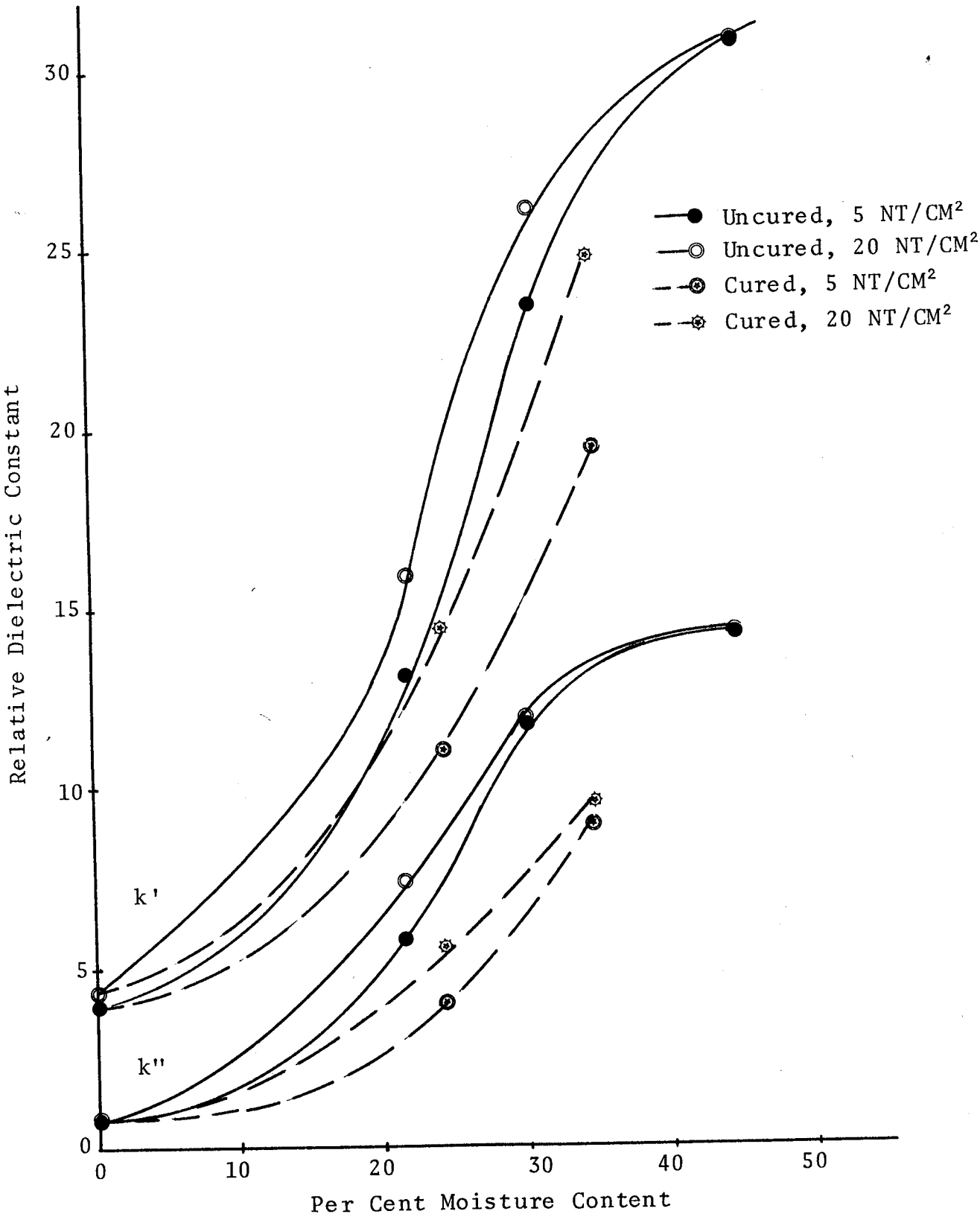


FIGURE 13. Houston Black Clay

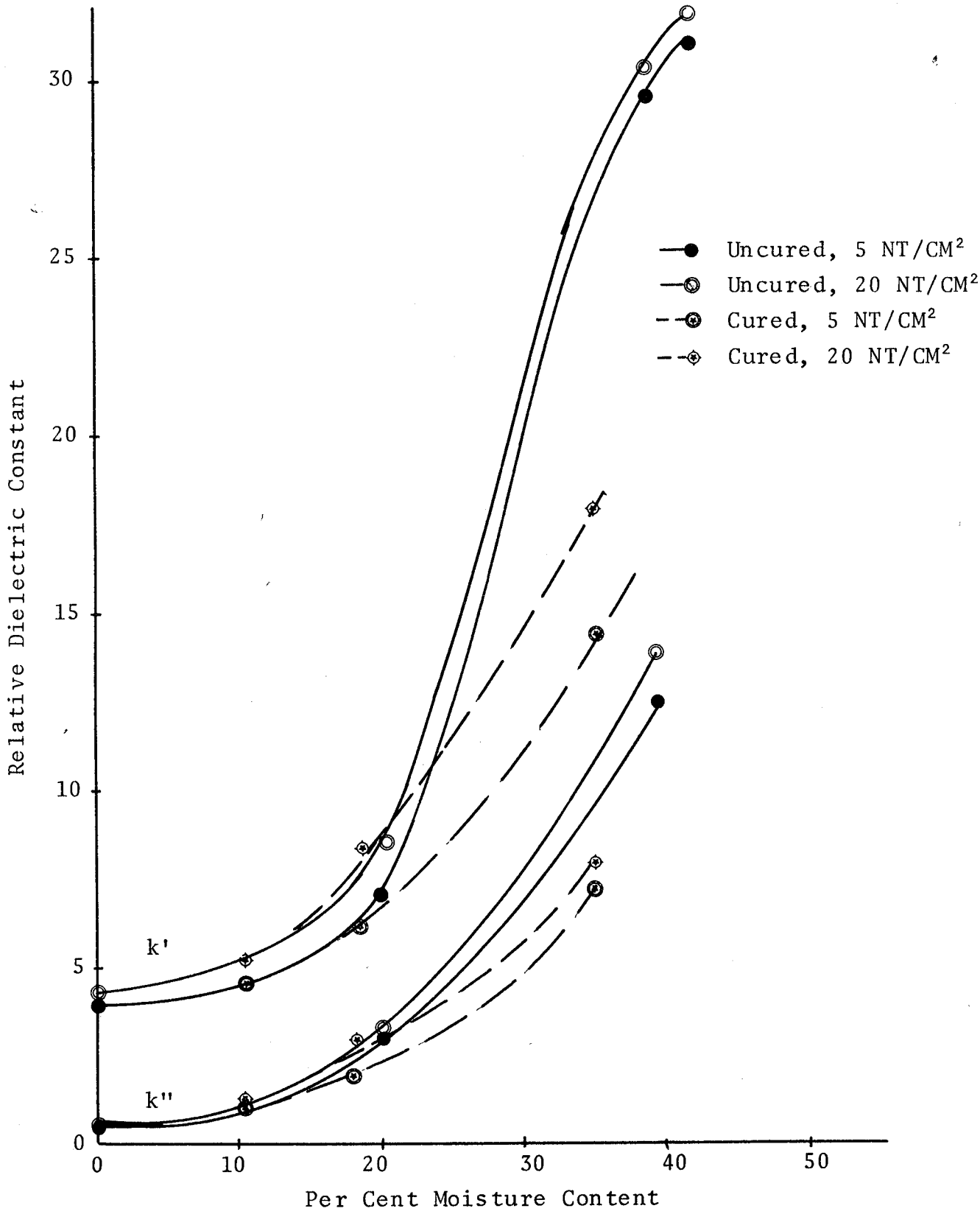


FIGURE 14. Miller Clay

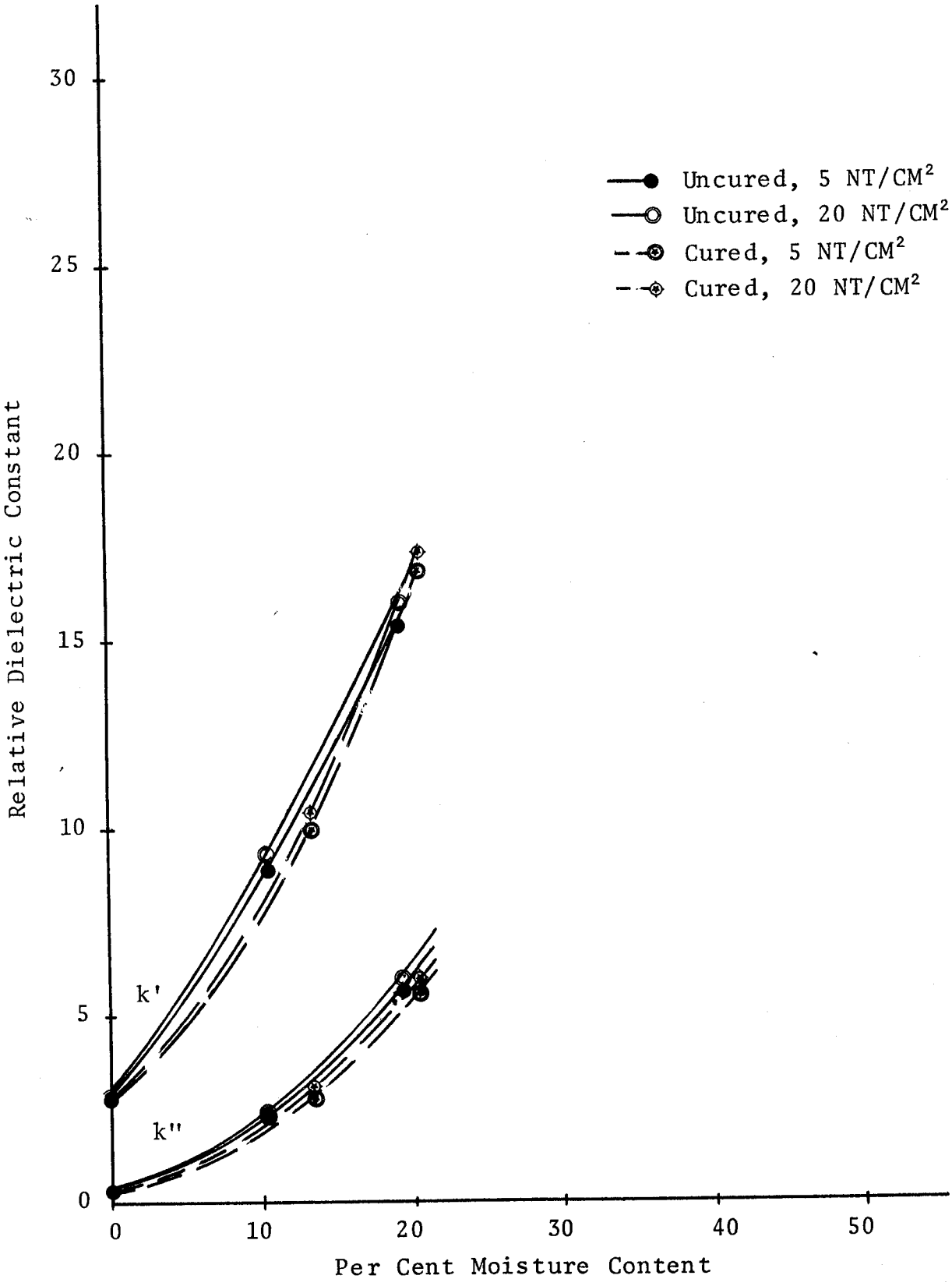


FIGURE 15. Robertson County Lake Sand

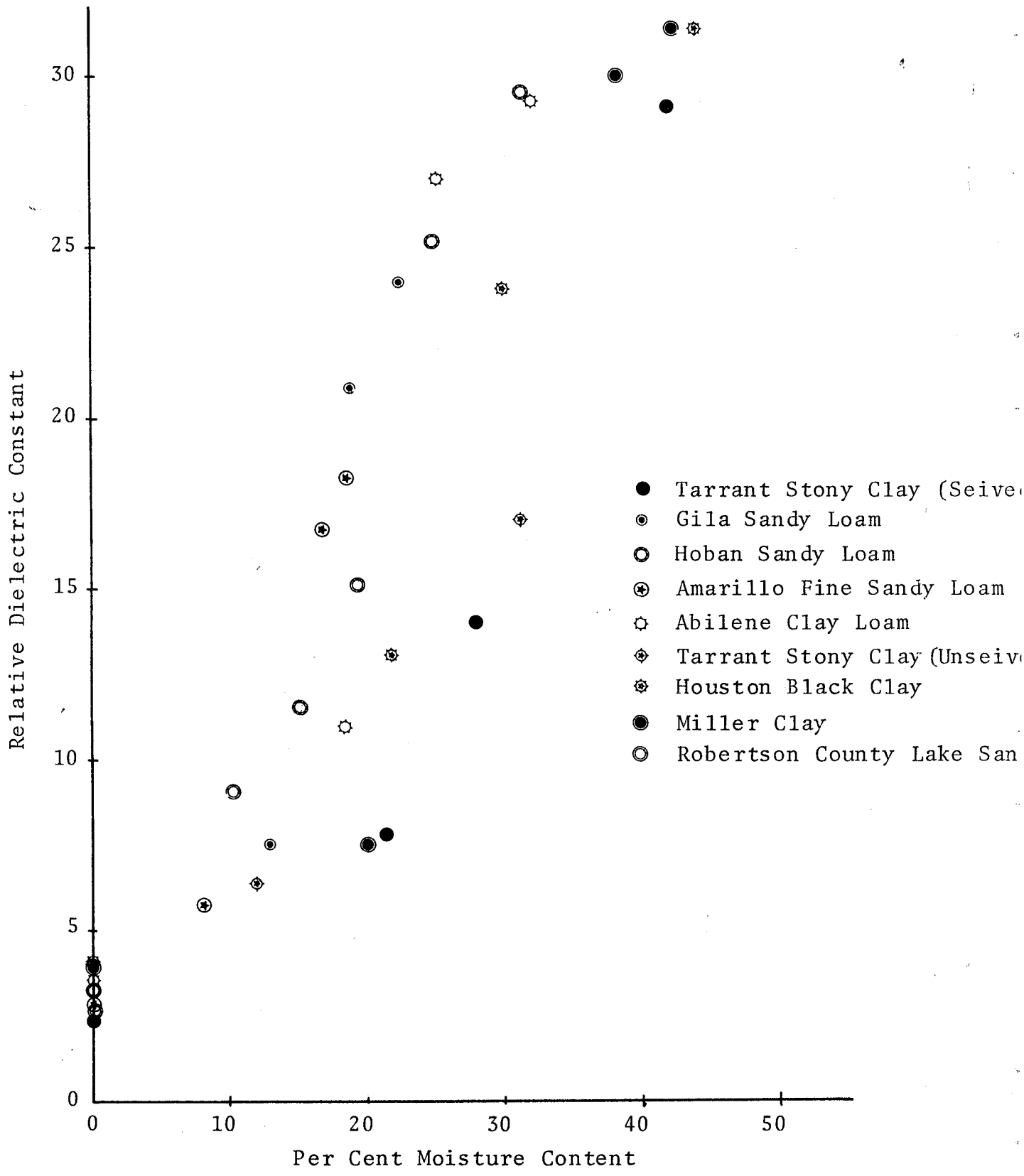


FIGURE 16. Real Part, All Soils Tested (Uncured), 5 NT/CM^2

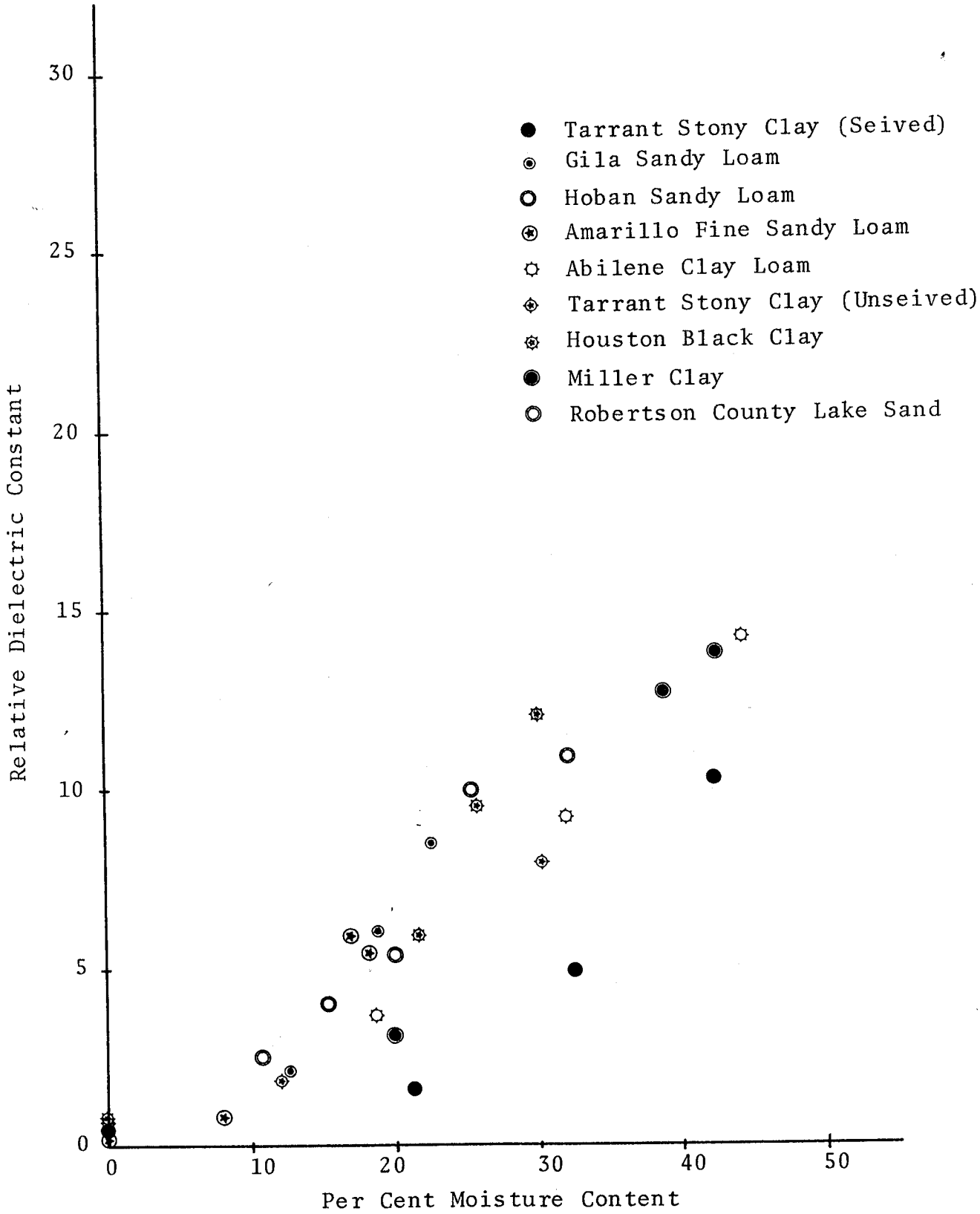


FIGURE 17. Imaginary Part, All Soils Tested (Uncured), 5 NT/CM^2

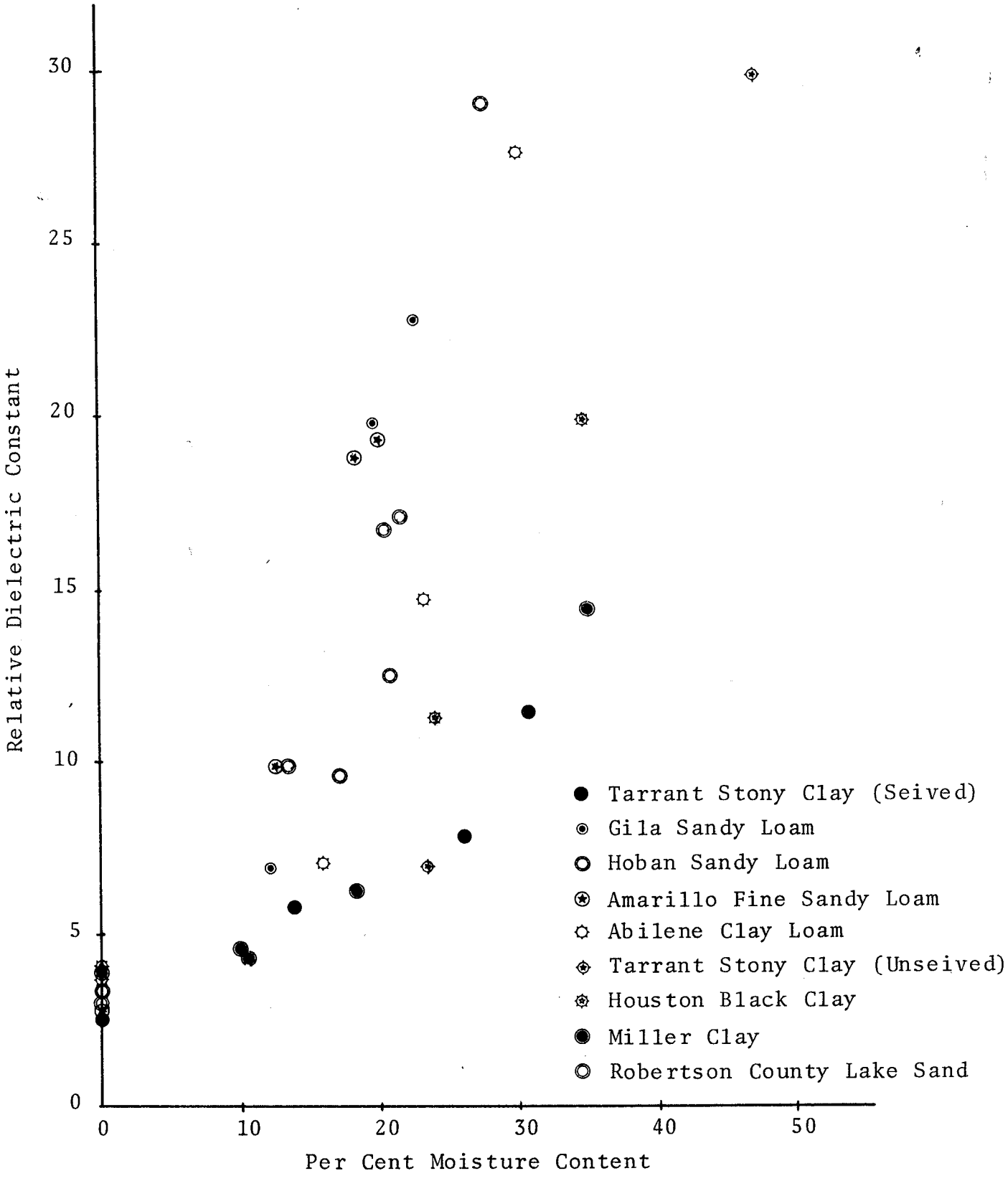


FIGURE 18. Real Part, All Soils Tested (Cured), 5 NT/CM^2

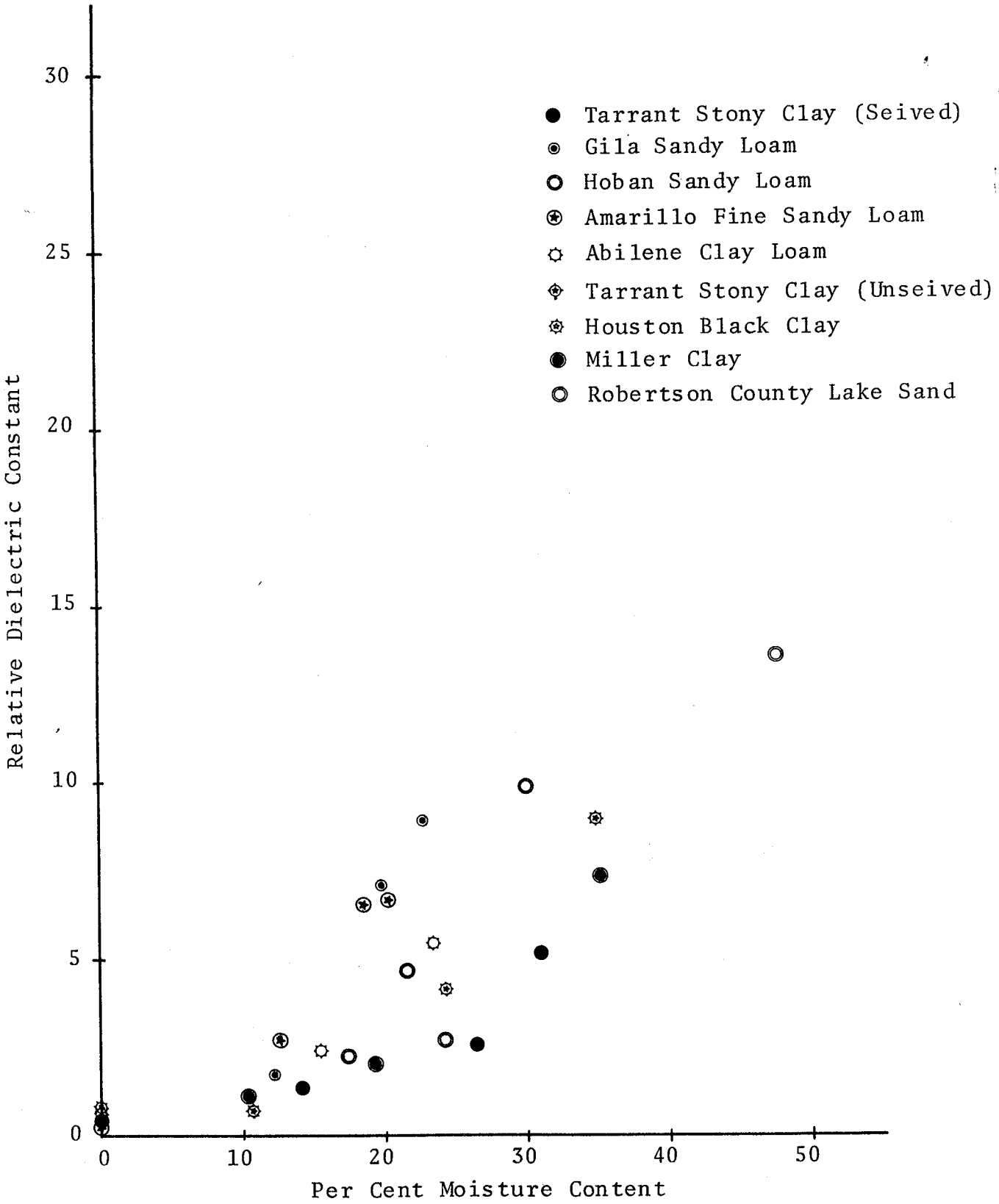


FIGURE 19. Imaginary Part, All Soils Tested (Cured), 5 NT/CM^2

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APPENDIX A

In order to facilitate rapid dielectric constant measurements on a large scale, the sample holder used must be of such nature that changing samples or incrementing sample lengths does not slow the procedure. The difficulties encountered in the measurements on sand at various moistures prompted a brief investigation into the area of holder design.

FREE SPACE HOLDER

Two types of holder designs were employed in the free space measurements. The first was a flat bottomed, cylindrical crystalizing dish as is used in chemistry laboratories. The diameter of the dish was slightly more than twice the widest dimension of the X-band receiving horn used. The depth was 9 centimeters allowing considerable variation in sample thickness. The surface of the sample was smoothed and leveled after adding material by sliding a bar across the top edges of the dish and allowing a perpendicular beam to just contact the surface sufficiently to even the depth. Then after each phase or attenuation reading the sample thickness was measured with

a depth guage.

While this method provided a reasonably rapid way of incrementing sample length, another holder was developed which proved more efficient. The second holder consisted of a rectangular teflon "box" with the top open and the top edges parallel to the bottom. The surface is smoothed in a manner similar to that described above, by sliding a bar across the top edges. In this case, however, the member which contacts the surface is constructed the same width as the holder, so only one pass is necessary. By constructing many such scrapers of specific depths, samples of known thicknesses may be prepared quickly and accurately.

GUIDE HOLDER

The problem of a sample holder within a section of waveguide is complicated by the requirement that firm contact be maintained between adjoining sections of the guide. Although this is normally accomplished by means of machine screws in the flanges, these can prove cumbersome when removing the sample holder for each length increment.

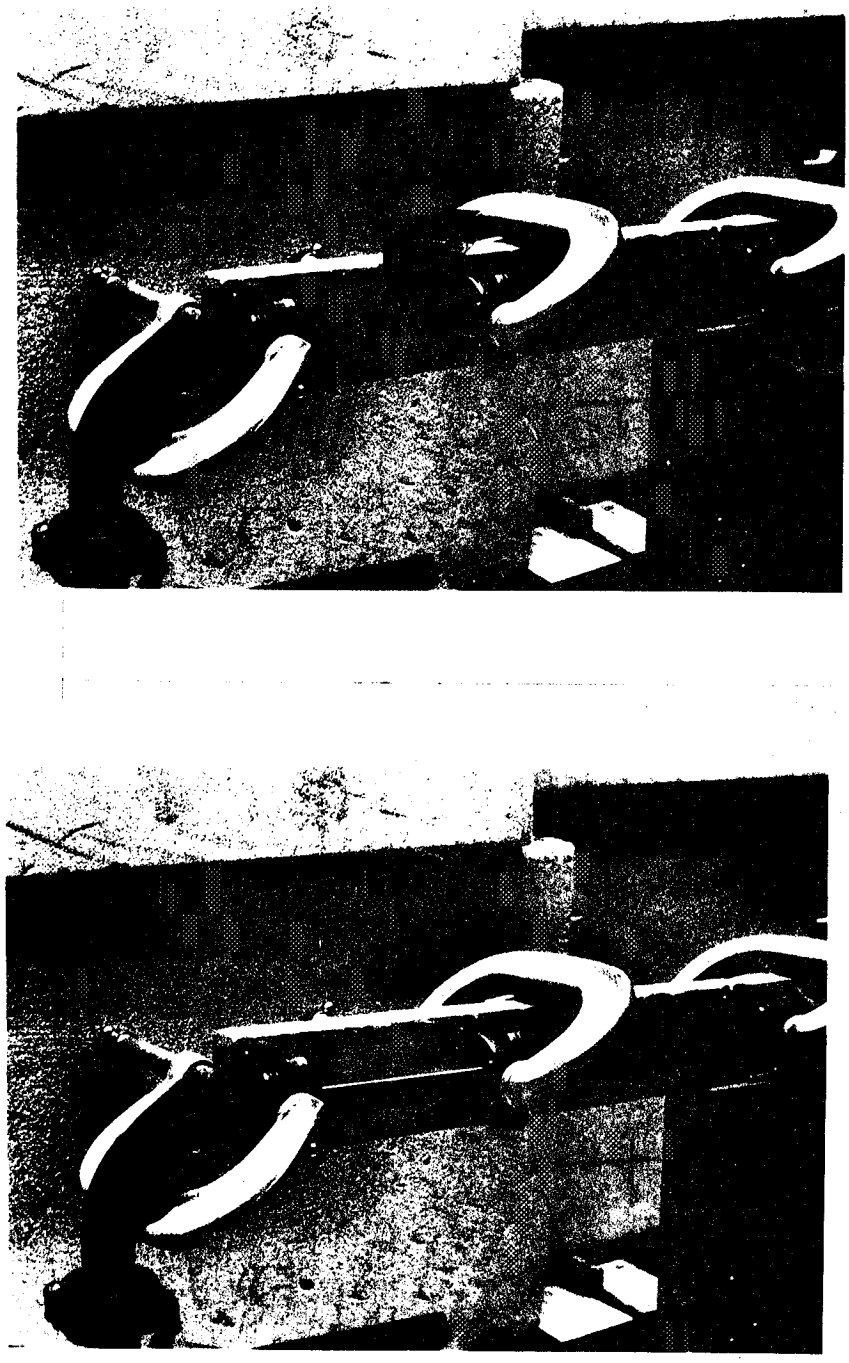

FIGURE A-1. Waveguide Sample Holder

The first holder used was made by positioning a teflon window at varius distances from the end of the guide, inserting the sample, and covering the end with cellophane tape. (By making the "empty" guide readings with the window and tape in place the "loaded" values measured will be due only to the sample.) While this provided a means of obtaining data, a great deal of time was consumed in changing samples. To increase the efficiency of the measurement technique, another holder was designed.

The second holder for the guide measurements consisted of a removable section of guide without flanges as shown in Figure A-1. The ends were milled smooth to insure good contact with the stationary guide, and the le length was slightly over size to insure a tight fit. Alignment of the holder with the rest of the guide was accomplished by means of wide tabs on the exterior of the stationary guide. A teflon window was placed at each end of the sample. The stationary guide was rigidly held by supports near the sample holder. This design made adjusting the sample extremely simple, as long as all sections of the guide were held rigidly in place to assure proper allignment.

The REMOTE SENSING CENTER was established by authority of the Board of Directors of the Texas A&M University System on February 27, 1968. The CENTER is a consortium of four colleges of the University; Agriculture, Engineering, Geosciences, and Science. This unique organization concentrates on the development and utilization of remote sensing techniques and technology for a broad range of applications to the betterment of mankind.