

TEMPERATURE EFFECTS ON DIELECTRIC CONSTANT DETERMINED BY TIME DOMAIN REFLECTOMETRY

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ABSTRACT

This paper addresses the effects of temperature on the apparent dielectric constant of compacted soils. Data are presented from tests on cohesive and noncohesive soils at various water contents and densities, tested at temperatures ranging from 4 °C to 40°C. Tests were performed on the soils placed with Standard Compaction Effort into a cylindrical mold that is used in compaction testing. Apparent dielectric constants were determined by inserting a steel rod along the axis of the specimen and using a Multiple Rod Probe Head, developed by the authors, in conjunction with a Tektronix® 4102B Cable Tester. The entire system was placed in a temperature controlled environmental chamber and measurements were made until readings stabilized, typically less than twenty-four hours. Test results reported here found that the apparent dielectric constant of compacted non-cohesive soils follow a similar, but less pronounced behavior as water, i.e. it decreases with increasing temperature. The opposite behavior was observed for compacted cohesive soils, whose apparent dielectric constant increase with increasing temperature. Recommendations are made to correct measured values of apparent dielectric constant to values at 20°C using simple linear corrections. It is shown that effects of temperature on water content determination likely to be small and can be neglected for temperatures within 5°C of 20°C.

INTRODUCTION

Temperature affects the dielectric properties of materials in different ways depending on the material. While this has been known for over 50 years (Frohlich (1949)), details of temperature effects on soils are still not well understood (Wraith and Or (1999)). If the apparent dielectric constant is used as a measure of dielectric properties, the apparent dielectric constant for water decreases with increasing temperature. The apparent dielectric constant for most soil solids is relatively independent of temperature in the range of 4°C to 40°C. It is reasonable to expect that the apparent dielectric constant for mixtures of soil solids and water also would exhibit a decrease in apparent dielectric constant with temperature, but to a lesser extent than for water alone. This holds true for cohesionless soils, but does not hold true for cohesive soils that have significant amounts of clay-sized particles. For these materials, the apparent dielectric constant increases with temperature. Some theories for this behavior were put forth by Wraith and Or (1999) and discussion of the theoretical behavior is beyond the scope of this paper.

This paper presents the results of an extensive series of tests to measure the apparent dielectric constant on a naturally occurring low plastic clay soil, pure kaolinite clay, pure illite clay, concrete sand, and fine sand. Each of the materials was compacted into a Standard Compact Test mold (ASTM D698) with standard compaction energy and with different water contents. With use of a guide template, a center conductor was driven into the specimens to form a soil "cable" with length equal to the height of the mold. A ring adapter and a Multiple Rod Probe Head (MRPH) were used to form a connection between the soil cable and a Tektronix® 4102B cable tester. Specimens were placed in an environmental chamber allowed to equilibrate to temperatures ranging from 4°C to 40°C. Measurements of apparent dielectric constant were made with time until readings stabilized.

The results of the tests are reported and are analyzed. Recommendations are put forth for correcting measured apparent dielectric constant to values at 20°C for cohesionless soils and for cohesive soils. The corrections are typically small and have a minor effect on calculation of water content.

Results from this work are important for improving the accuracy of the TDR method for measuring the water content and density of soils as described by Feng *et al.* (1998), Lin *et al.* (1998), Lin *et al.* (2000), Siddiqui and Drnevich (1995), Siddiqui *et al.* (2000), and Drnevich *et al.* (2001).

TEST PROCEDURES AND TEST RESULTS

Soils Tested

Tests were conducted on three cohesive and two noncohesive soils the properties of which are given in Table 1. The samples were classified according to ASTM D2487, the Unified Soil Classification, their Atterberg Limits (plastic and liquid limits) tested according to ASTM D4318, and their compositions determined by ASTM D422. The authors are grateful to Mr. Jie Zhang who performed most of the tests.

The Crosby Till soil is an inorganic silty-clay having low to medium plasticity. It is a naturally occurring soil found in the vicinity of the Purdue University campus. The Kaolinite and Illite samples were pure clay minerals. The kaolinite had slight plasticity and the illite had moderate to high plasticity.

The noncohesive soils included a concrete sand that is naturally occurring but has been washed to remove fines. Tests were also conducted on a fine Ottawa sand, which was commonly used in cement and concrete research.

Test Specimens

Tests were performed on specimens placed in a Standard Compaction Mold (ASTM D698) that had a diameter of 101.6 mm (4.0 in.) and a height of 116.4 mm (4.584 in.) giving a volume of $9.19 \times 10^5 \text{ mm}^3$ (1/30 ft³). For all soil specimens, the soil specimens were compacted with standard compaction effort 600 kN-m/m³ (12,400 ft-lb/ft³) at a variety of different water contents (gravimetric) ranging from below optimum to above optimum.

Once a specimen was compacted and the mass of the specimen and mold were determined, the metal bottom plate was replaced with a non-metallic plate. Then a guide template was temporarily placed on top of the mold and a stainless steel center rod with diameter of 7.94 mm (5/16-in.) was driven into the specimen over its full height (See Fig. 1.). When the guide was removed, the rod protruded from the soil surface by approximately 30 mm (1.2 in.). An adapter ring was then

Table 1. Characteristics of Soils Tested

Soil	Unified Soil Classification	Atterberg Limits		Composition		
		Liquid Limit	Plastic Limit	% sand	% silt	% clay
Crosby Till	CL	41	18	16	50	34
Kaolinite	CL-ML	30	24	0	0	100
Illite	CL-CH	50	22	0	0	100
Concrete Sand	SW	NA	NA	100	0	0
Fine Sand	SP	NA	NA	100	0	0

placed on the top of the compaction mold as shown in Fig. 2. The ring presented a surface for the outer three legs of the Multiple Rod Probe Head (MRPH) to be supported. The center rod of the MRPH then came in contact with the center rod as shown in Fig. 3.

TDR measurements were made with this arrangement by connecting MRPH with a Tektronix 8102B Cable Tester with a 1 m (3-ft.) coaxial cable with BNC connectors on each end.

Additional information about the use of this equipment for determining the apparent dielectric constant, K_a , is available in a companion paper to this conference by Drnevich *et al.*(2001).

One set of tests was done with the mold filled with water to validate that test results were consistent with test reported in the literature.

Test Environment

Three separate walk-in environmental test chambers were used for tests at 4°C, 10°C, and 20°C where temperatures were reasonably close to the set temperatures for the test duration.



Fig. 1. Center Rod Being Driven into Specimen Through Guide Template



Fig. 2. Mold with Center Rod and Adapter Ring Ready for Multiple Rod Probe Head



Fig. 3. Multiple Rod Probe Head Ready for Making TDR Measurements

For temperatures of 30°C and 40°C, the specimens were placed in a large drying oven where temperatures were maintained within ±1°C of the preset temperature.

Between times when readings were made, the specimens were covered with a plastic film to minimize the amount of moisture lost between readings. Determinations of total mass of the soil, mold, and center rod at the time of each TDR reading allowed for checking any changes in specimen water content.

Testing Sequence

All specimens were constructed at room temperature, 20°C and then placed into the environmental chamber for testing. TDR readings were taken as a function of time to obtain the time required for equilibration. Most of the tests at a given temperature were on specimens tested only at that temperature. An example of this is shown in Fig. 4 for tests on Crosby Till at a target water content of 21 percent. Note that it typically took up to 1000 minutes for the readings to stabilize for the size specimens tested in these experiments.

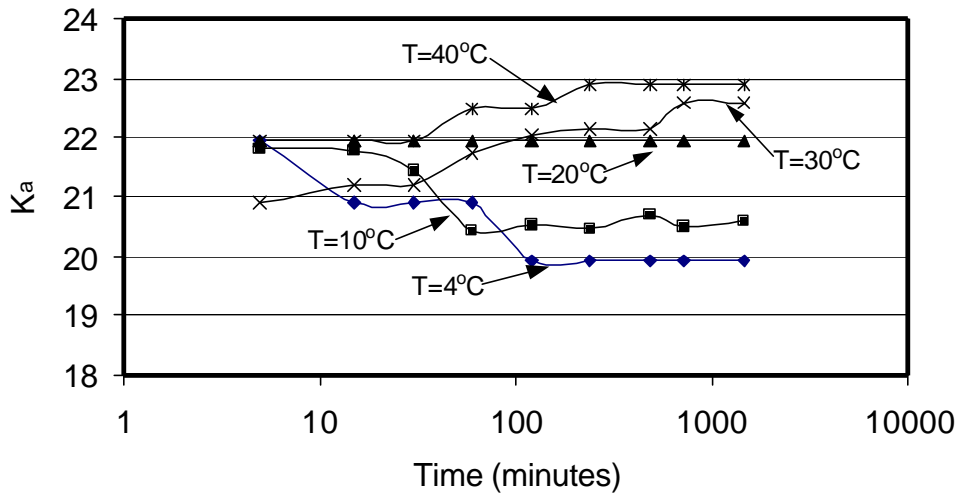


Fig. 4. Apparent Dielectric Constant of Crosby Till at a Target Water Content of 21% with Tests at All Temperatures Done with Separate Soil Specimens for Each Temperature.

A given specimen could be tested at different temperatures without significantly affecting the results and some of the measurements were made at multiple temperatures ranging from 4°C to 40°C. Figure 5 gives an example of measurements made at three temperatures on a specimen of Crosby Till with a water content of 41 percent.

The typical testing process involved measurements at 4°C, 10°C, 20°C, 30°C, and 40°C. On some of the soils, testing at some of the temperatures was omitted for saving of time since equilibration at each temperature took approximately 24 hours. On several of the clay soils at high water content and at high temperatures, accurate apparent length measurements could not be made because the soil was too lossy, i.e. dissipated the signal so that no reflected signal could be detected.

The mass of soil and compaction mold was measured at each time a TDR measurement was made. At the end of the test, oven drying was used to determine water content (ASTM D2216). The mass measurements made along with the TDR measurements were used to calculate the water contents at the time of measurement. Table 2 gives the information on water contents, dry densities, and apparent dielectric constant for the soils tested. The water contents in Table 2 are **gravimetric** water contents. Agronomists make extensive use of TDR for measuring the **volumetric** water content of soil (volume of water as a percentage of the total volume of the soil). The volumetric water content is usually represented by the Greek letter theta, q . Geotechnical engineers work with the **gravimetric** water content of soil (mass of the water/mass of dry solids) and it is usually represented by the letter, w . Both q and w are expressed as percentages. Volumetric and gravimetric water contents are related by

$$w = q \frac{r_w}{r_d} \quad (1)$$

where r_d is the dry density of the soil and r_w is the density of water.

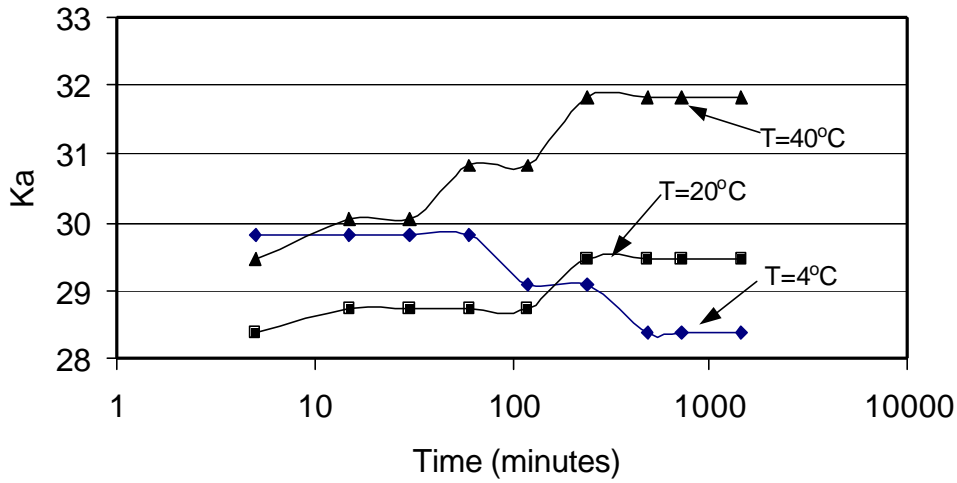


Fig. 5. Apparent Dielectric Constant of Crosby Till at a Target Water Content of 41% with Measurement at Different Temperatures Made on the Same Soil specimen.

Tests on Water

Figure 6 presents the results for tests on water. Data from Weast (1986) and Mitchell (1993) also are plotted in this figure. The test results compare fairly well with the greatest discrepancy occurring at a temperature of 40°C where the difference is about three percent.

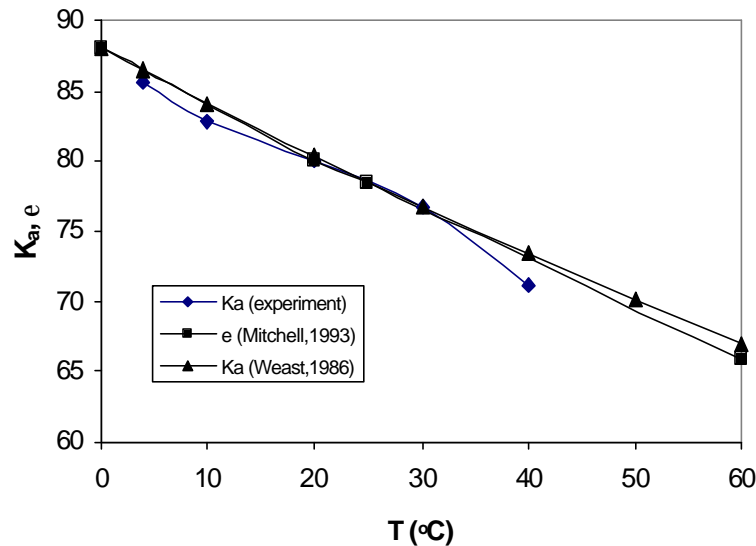


Fig. 6. Apparent Dielectric Constant Variation with Temperature for Water

Table 2. Testing Program and Results of Tests on Soils

Soil	Target Water Content (%)	Actual Water Content (%)		Temperature of Testing (°C)					
		Dry Density (Mg/m ³)		4	10	20	30	40	
		K _a							
Crosby Till	3	Water Content		3.1		2.0		3.0	
		Dry Density		1.543		1.543		1.543	
		K _a		4.121		4.335		4.481	
	12	Water Content		11.6	12.0	11.1	11.8	11.9	
		Dry Density		1.713	1.713	1.713	1.722	1.706	
		K _a		11.940	12.348	12.740	13.660	13.976	
	15	Water Content		14.4	14.8	13.9	13.8	14.8	
		Dry Density		1.769	1.748	1.759	1.701	1.759	
		K _a		15.240	16.124	16.578	17.960	18.920	
	18	Water Content		16.8	17.2	16.6	17.1	17.9	
		Dry Density		1.789	1.782	1.788	1.782	1.788	
		K _a		17.965	19.415	19.906	21.634	21.946	
	21	Water Content		20.4	20.8	20.0	20.9	20.5	
		Dry Density		1.713	1.694	1.715	1.660	1.715	
		K _a		19.906	21.430	21.946	22.367	22.875	
	24	Water Content		22.7	23.0	22.3	22.8	23.7	
		Dry Density		1.623	1.618	1.638	1.625	1.638	
		K _a		20.914	21.946	23.004	25.19	26.32	
	41	Water Content		39.0		39.0		38.35	
		Dry Density		1.280		1.280		1.280	
		K _a		28.558		29.458		31.829	
	Kaolinite	20	Water Content		20.6		20.5	20.2	
			Dry Density		1.505		1.505	1.505	
			K _a		20.039		20.982	21.301	
30		Water Content		28.2		28.1			
		Dry Density		1.455		1.455			
		K _a		22.601		23.602			
40		Water Content		43.4		43.2	42.6		
		Dry Density		1.221		1.221	1.221		
		K _a		31.214		31.994	33.182		
Illite	20	Water Content		19.2		19.1	18.9		
		Dry Density		1.626		1.626	1.626		
		K _a		25.998		28.803	31.571		
	45	Water Content		45.4					
		Dry Density		1.17					
		K _a		36.114					
	50	Water Content		50.1		50.1	49.7		
		Dry Density		1.15		1.15	1.15		
		K _a		47.911		49.037	51.096		
Concrete Sand	0.2	Water Content		0.20		0.20		0.20	
		Dry Density		1.785		1.785		1.785	
		K _a		3.643		3.643		3.511	
	14.6	Water Content		14.5		14.5		13.7	
		Dry Density		1.883		1.883		1.883	
		K _a		18.515		17.923		16.875	
Fine Sand	0.08	Water Content		.08		.08		.03	
		Dry Density		1.682		1.682		1.682	
		K _a		2.66		2.66		2.66	
	19.4	Water Content		19.4		19.4		18.8	
		Dry Density		1.742		1.742		1.742	
		K _a		21.622		20.982		19.729	

ANALYSIS OF THE RESULTS AND RECOMMENDATIONS

Normalized Apparent Dielectric Constant

The apparent dielectric constant data in Table 2 were normalized by dividing each of the values for a soil at a target water content by its corresponding value at 20°C. The results are plotted in Fig. 7. Also plotted in this figure are the normalized data for water. Note that the curve for water exhibits the most dramatic decrease with increase in temperature. The sand soils also exhibit a decrease in apparent dielectric constant with increase in temperature but the decrease is less dramatic. For sands with near zero water content, there is no appreciable change in apparent dielectric constant with temperature.

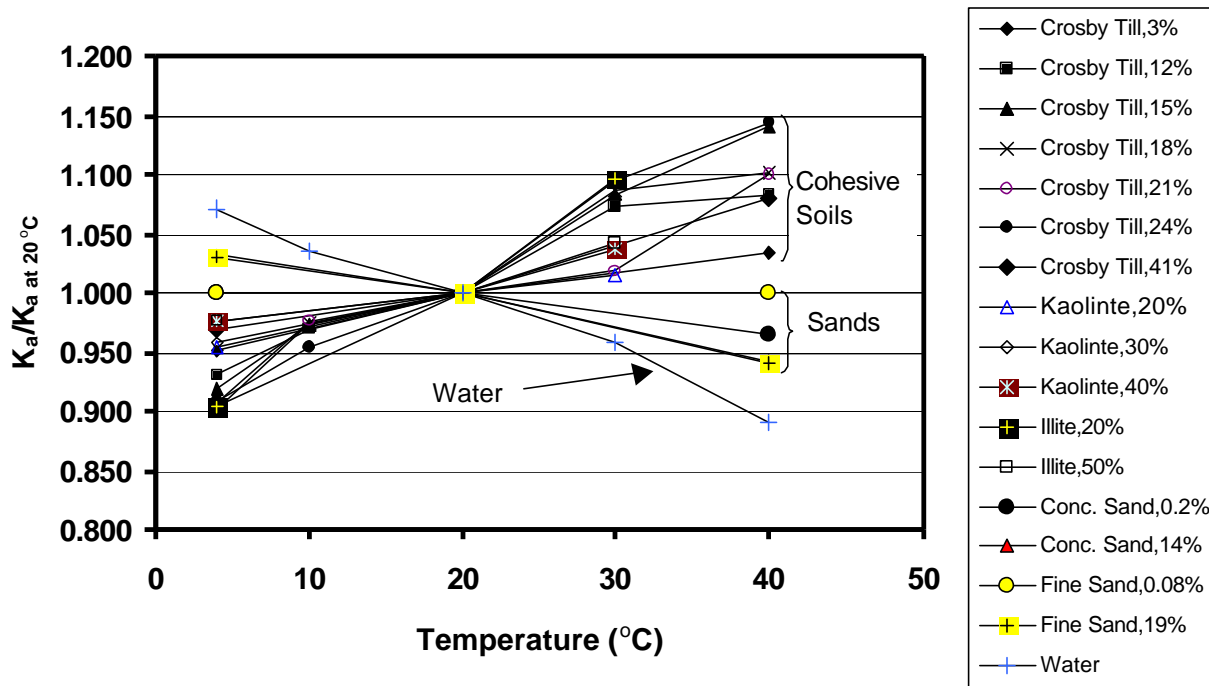


Fig. 7. Normalized Apparent Dielectric Constants for Water and All Soils Tested.

The behavior of cohesive soils plotted in Fig. 7 shows the opposite trends from those of water and sands; the dielectric constant increases with increasing temperature. Wraith and Or (1999) and other suggest that this behavior is due to the bound water typically associated with fine-grained soils. A detailed discussion of these phenomena is beyond the scope of this paper.

Effects of Water Content on Behavior of Cohesive Soils

For the soils tested, an attempt was made to discern effects of different water contents on values of apparent dielectric constant. This was done by fitting a straight line by least squares fitting through each of the data sets for the cohesive soils in Fig. 7. Then the slopes of each of these lines were plotted versus water content. Figure 8 presents the results for Crosby Till. The data in Fig. 8 are fitted with a second order polynomial to help accentuate the trend. The slope of these lines increases with increasing water content to peak and then the slope starts to decrease at higher water contents. It was argued that at very low water contents, the soil solids and the bound water control the behavior. With increasing water content, free water becomes an increasingly large component of the total volume and the effects of temperature on free water begin to dominate.

Note that the curve in Fig. 8 peaks near the Plastic Limit (ASTM D4318) for this soil, which was 18 percent. It was conjectured that below the Plastic Limit, not much unbound water is available to promote plastic behavior of soil and that this might be related to the amount of water available to affect the dielectric properties with temperature. Hence, the Plastic Limit became a candidate for normalizing the water content for the purposes of studying the behavior of all cohesive soils. In Fig. 9 are plotted all of the slope data versus water content normalized by the Plastic Limit for these tests on cohesive soils. While the data set available contains too few types of cohesive soils from which to draw any strong conclusion, plotting of future data in the same manner may provide some useful insight into the phenomena. For example, it appears that the peak in the slopes occurs at water contents approximately 1.3 times the Plastic Limit.

Considering that temperature effects on dry soil solids are near zero, the corresponding slope of $K_a/K_{a,20^\circ C}$ would go through origin in Figs 8 and 9. Likewise, as water content gets very large, the slopes would become negative and eventually be asymptotic to the slope for water (-0.354 after Weast (1986)).

Temperature Adjustments to Measured Values of Apparent Dielectric Constant

The values of normalized apparent dielectric constant for the cohesive soils in Fig. 7 were averaged at each temperature. These averaged values were then plotted versus temperature to obtain a mean curve that might apply to all of the cohesive soils tested. The same process was applied to all of the sand data in Fig. 7 as well. The data for both the cohesive soils and the sand soils turned was exceptionally linear.

For practical purpose, we are recommending that effects of temperature on apparent dielectric constant can be accommodated by simple linear correction as given in Eq. (2).

$$K_{a,20^\circ C} = K_{a,T^\circ C} \times TCF \tag{2}$$

where

TCF = Temperature Correction Function

$$= 0.97 + 0.0015 T_{test, T^\circ C} \text{ for cohesionless soils, } 4^\circ C \leq T_{test, T^\circ C} \leq 40^\circ C$$

$$= 1.10 - 0.005 T_{test, T^\circ C} \text{ for cohesive soils, } 4^\circ C \leq T_{test, T^\circ C} \leq 40^\circ C.$$

From Eq. (2) it can be seen that values of $K_{a,20^\circ C}$ will not exceed about three percent for cohesionless soils and ten percent cohesive soils for extremes in temperature covered by this equation.

The theoretical and experimental study by Lin et al. (2000) suggested that the density-compensating calibration equation proposed by Siddiqui and Drnevich (1995) provides the best relationship between soil water content and apparent dielectric constant. The ‘‘Siddiqui-Drnevich’’ calibration equation accounts for soil density and soil type:

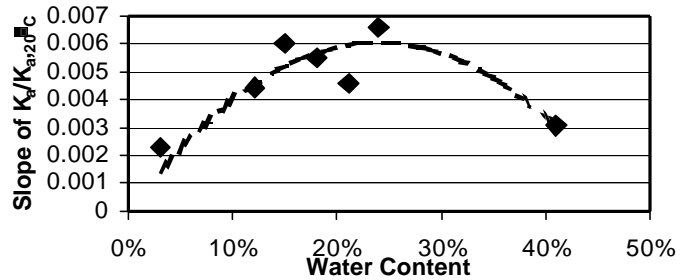


Fig. 8. Change of Slope of Normalized Temperature Effects Lines with Water Content for Crosby Till

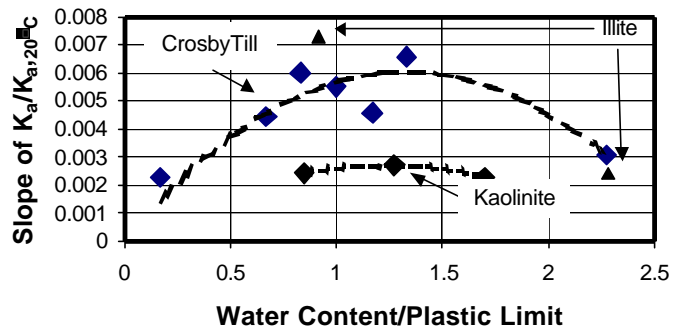


Fig. 9. Slope of Normalized Apparent Dielectric Constant with Water Content Normalized by the Plasticity Limit

$$w = \frac{1}{b} \left[\frac{r_w}{r_d} \sqrt{K_a} - a \right] \quad (3)$$

where r_d is the dry density of soil, r_w is the density of water, a and b are soil-dependent calibration constants. From tests on a variety of soils the value of a is consistently near unity and the value of b is consistently near eight. Considering Eq. (3), we see that water content is related to the square root of K_a and hence temperature effects on water content are relatively small. The authors suggest that temperature corrections are not needed for $15^\circ\text{C} \leq T_{est}, T_C \leq 25^\circ\text{C}$. This recommendation and the correction recommended in Eq. (2) are consistent with the findings of Kuraz (1981) who stated, "Temperature effects may be neglected for fluctuations of 5°C . For wider changes in temperature, a simple linear correction is required."

SUMMARY AND CONCLUSIONS

Apparent dielectric constants in soils are somewhat dependent on soil temperature. Data are presented from tests on cohesive and noncohesive soils at various water contents and densities, measured at temperatures ranging from 4°C to 40°C . Test results show that apparent dielectric constant for sands decrease with increasing temperature similar to the behavior observed in water, but less dramatic. For clays, the opposite behavior was observed, i.e. the apparent dielectric constant increased with increasing temperature. The amount of correction for clays depends on the water content and there exists a water content just higher than the Plastic Limit where temperature effects are the largest. Recommendations are made to correct measured values of apparent dielectric constant to values at 20°C using simple linear corrections. It is shown that effects of temperature on water content determination are likely to be small and can be neglected for temperatures within 5°C of 20°C .

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