

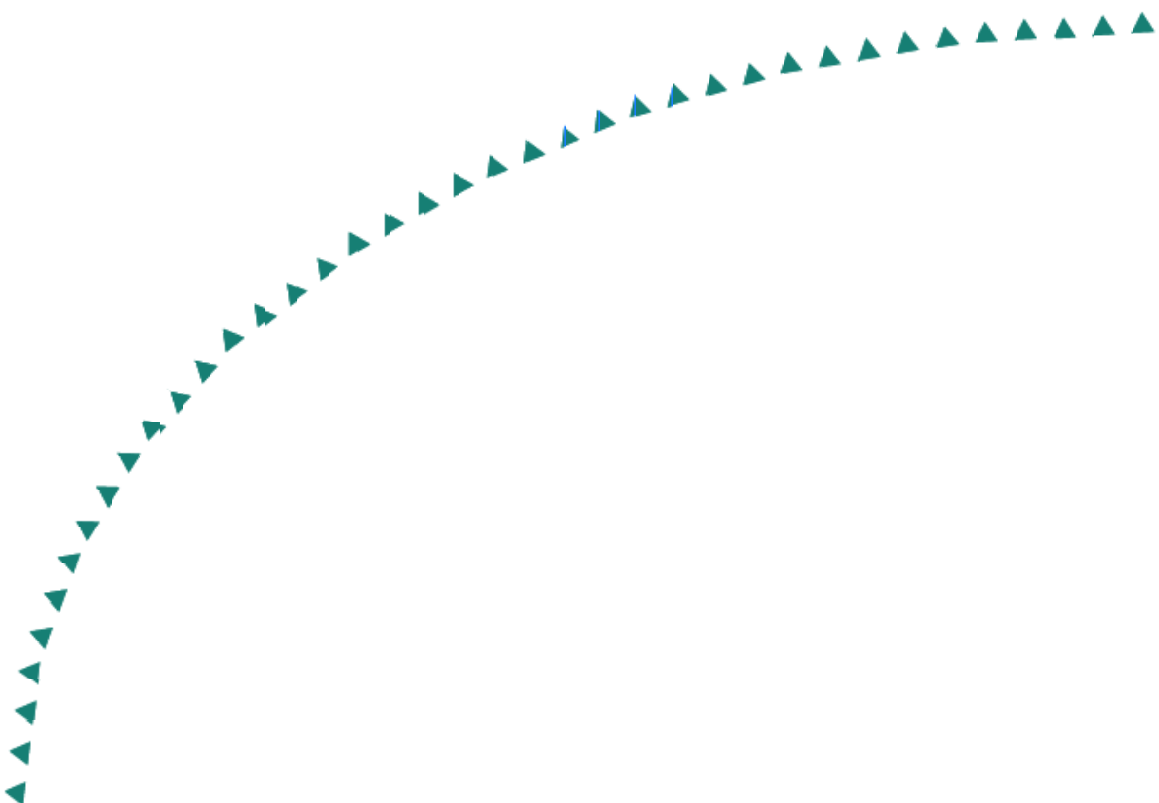
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Final Report

**Mn/ROAD TDR Evaluation
and Data Analysis**



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Mn/ROAD TDR Evaluation and Data Analysis

Final Report

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Table of Contents

Chapter 1. Introduction.....	1
Chapter 2. Particle Size Distribution and Water Retention of Pavement Materials	2
Chapter 3. Development of a Theoretical Relationship Between Water Content and Apparent Dielectric Constant and Temperature.....	5
Chapter 4. TDR System Calibration: Dielectric Constant of Water as a Function of Temperature.....	7
Chapter 5. Test Scenarios and Parameter Determination with Water Content as a Function of Dielectric Constant and Temperature.....	9
Chapter 6. Conclusions	13
Chapter 7. Recommendations.....	14
References.....	15
Appendix A: Dielectric Constant of Mn/ROAD Materials as a Function of Temperature and Water Content	A-1

List of Figures

Figure 1.1 Soil Temperature at 63 cm Depth Under Mn/ROAD Cell 6 (Subgrade, data from the Minnesota Department of Transportation [Mn/DOT]).	2
Figure 2.1 Particle-size Distribution of Mn/ROAD Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) materials (Data from Mn/DOT).	3
Figure 2.2. Water Retention of Mn/ROAD Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) materials.	4
Figure 4.1 Dielectric Constant of Water as a Function of Temperature.....	7
Figure 4.2 Water Temperature Near the Top and Bottom of a Bucket Used for TDR System Calibration.....	8
Figure 5.1. Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.	9
Figure 5.2. Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.....	10
Figure 5.3. Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.....	10
Figure 5.4 Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.....	11

List of Tables

Table 5.1. Test Scenarios and Parameters for Determination of Water Content as a Function of Dielectric Constant and Temperature.....	12
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Executive Summary

Water content measurement using time domain reflectometry (TDR) is an important integral component of the Minnesota Road Research Project (Mn/ROAD) program. However, erroneous and inaccurate water content values are frequently generated using current data collection and interpretation procedures. Whereas the erroneous and obviously unreasonable values are caused by limitations of the current waveguide/cable systems, inaccurate water content values are most likely caused by the inadequacy of the empirical calibration equations. Base, Subbase, and Subgrade materials are different from agricultural soils in composition, water retention characteristics, and more importantly in their dielectric properties in relation to water content and temperature regimes in the road pavement. This project was to develop a new composition-based calibration between water content and apparent dielectric constant of the pavement materials. Temperature effect on the dielectric constants of water and pavement components was also integrated in the new calibration. Results indicated that the new calibration was more theoretically sound and relatively simple to use. Additional tests and developments may be needed to further validate the reliability of the new approach.

Chapter 1. Introduction

Minnesota Road Research Project (Mn/ROAD) water content measurements using time domain reflectometry (TDR) and current calibration procedures frequently generate erroneous water content values. The problem appears to be attributed to several factors. A comprehensive evaluation by Roberson and Cahoon (1998) created a complete classification on the reliability of all waveguides/cable connections. Some of the waveguide/cable combinations are likely permanently damaged (no return signal) that will not provide water content measurement until repaired and reinstalled. Others are unreliable because they produce waveforms without a distinctive inflection point. This is likely caused by an excessive signal reduction in the high-clay content/conductivity Subgrade materials or long cables. Modifications to waveguide/cable configurations, such as shortening (Wang et al., 1998) or coating the waveguide with a less conductive layer and/or reducing the cable length may be required. Waveguide/cable combinations that can produce waveforms with distinctive inflections are classified as “good”, and water content values can be generated using an empirical calibration. However, the accuracy or the inaccuracy of the water content values generated from the “good” waveguides is very important because associated uncertainties will propagate when the water content data is used in other applications.

It is well recognized that water content measurements using TDR are relatively more reliable in coarse-textured sandy soils than in fine-textured clayey soils. Applications of TDR in soils with high clay content are more susceptible to restrictions on probe length and weakening of return signals. The effect of fine particles on TDR was attributed to the increased particle surface area and amount of bound water (Logsdon, 2000). A large portion of the Subgrade materials used in Mn/ROAD has a relatively high clay content (comparable to a clay loam) and possibly a high electrical conductivity; both would increase the difficulty of measuring water content using TDR. In light of differences between agricultural soils and the Base, Subbase, and Subgrade materials, calibration equations have been generated in several previous projects. However, all existing calibrations are empirical, of the same linear form of Ledieu et al. (1986), with a slight variation in values for the slope and intercept. Because major differences between the Base, Subbase, and Subgrade are particle composition and total porosity, a new calibration method to account for textural differences (Malicki et al., 1996) would unify the empirical models and likely provide a more robust calibration between the bulk apparent dielectric constant and water content.

The dielectric constants of water and soil components are temperature dependent. Subsurface temperature under a pavement can be highly variable diurnally and seasonally because of lack of evaporative cooling at the surface. For example, temperature in the Subgrade experienced a 30 °C change even at 63 cm from the surface (Fig. 1). The dielectric constant of water would be 15% lower when temperature increases from 0 °C to 30 °C according to a theoretical relationship found in Zegelin et al. (1992). A temperature correction for water and all solid materials is needed in the calibration. The temperature range should also cover the whole spectra of likely temperatures in the subsurface under a pavement.

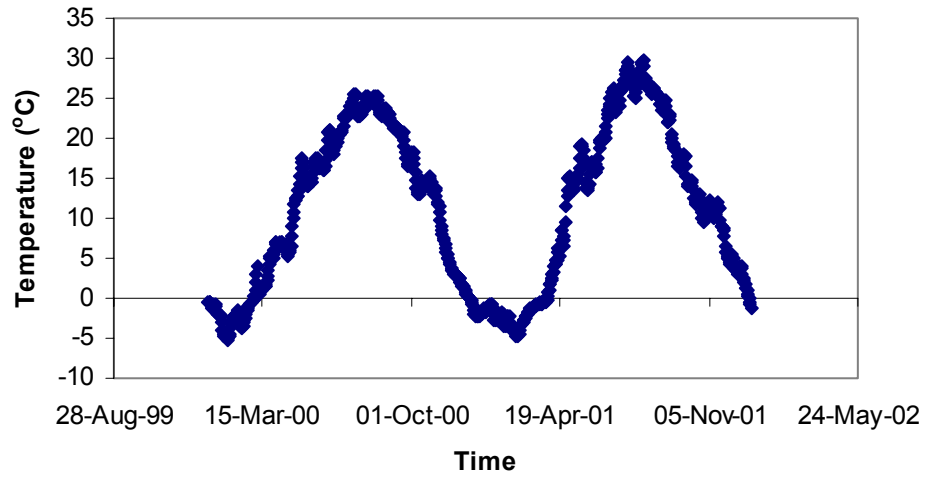


Figure 1.1 Soil temperature at 63 cm depth under Mn/ROAD Cell 6 (Subgrade, data from the Minnesota Department of Transportation [Mn/DOT]).

The overall objective of this project was to address inherent differences between the Mn/ROAD Base, Subbase, and Subgrade materials in order to improve water content measurement with TDR. To achieve this overall goal, following specific objectives were identified:

- 1) To develop a new composition-based calibration between water content and apparent dielectric constant of the Base, Subbase, and Subgrade materials.
- 2) To establish and integrate temperature effects on the dielectric constants of water and components of the pavement materials in the new calibration.

Chapter 2. Particle Size Distribution and Water Retention of Pavement Materials

Solid particles of the pavement materials are of different mineral composition. Whereas most rock fragments are sandstones, gravels are sedimentary origin. Sand and silt are likely quartz derivatives. Clays can also belong to three primary groups: Kaolinite, Illite, or Montmoriculite. Because these minerals have distinctive dielectric constant values, differences in particle size distribution likely will affect the bulk dielectric constant especially when the material is free from water. To help delineate the particle size distribution needed for the development of a new composition-based calibration (objective 1), particle size data of the Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) were provided by Mn/DOT. The data were analyzed and presented in a texture graph (Fig. 2). According to the USDA classification scheme, particles with diameter greater than 0.05 mm were sand, 0.002 to 0.05 mm were silt, and smaller than 0.002 were clay. The Subgrade had 21% clay, but the Subbase and Base materials contained insignificant amount clay.

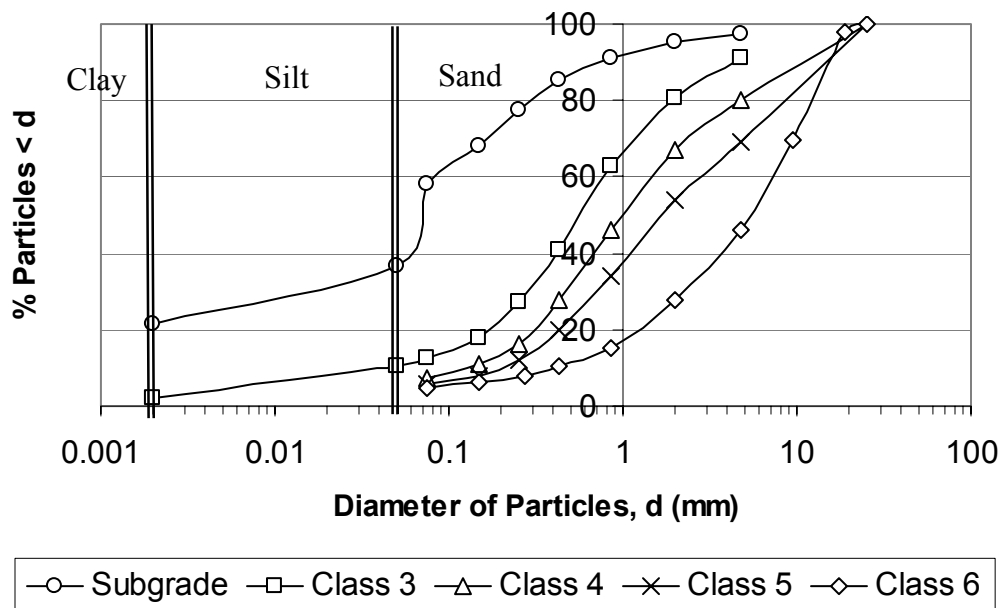


Figure 2.1 Particle-size distribution of Mn/ROAD Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) materials (Data from Mn/DOT).

Water retention is a description of the functional relationship between water content and matric potential of a porous material. The relationship is related to pore or particle size distribution, and in some instances pedotransfer functions may be used to infer water retention from only particle size information.

Because water retention provides a direct measurement of the behavior of a porous material in terms of imbibition and drainage processes and no existing data were

available for the Mn/ROAD pavement materials, laboratory experiments were carried out to determine the water retention curves for the Mn/ROAD Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) materials. Pressure plates were used for the laboratory experiments and the same procedure was followed for all the tests. Consistent with the particle size data, the retention curve of the Subgrade showed, compared to the Subbase and Base materials, a significantly higher water holding capacity and slower water release with increasing pressure (Fig. 2.2).

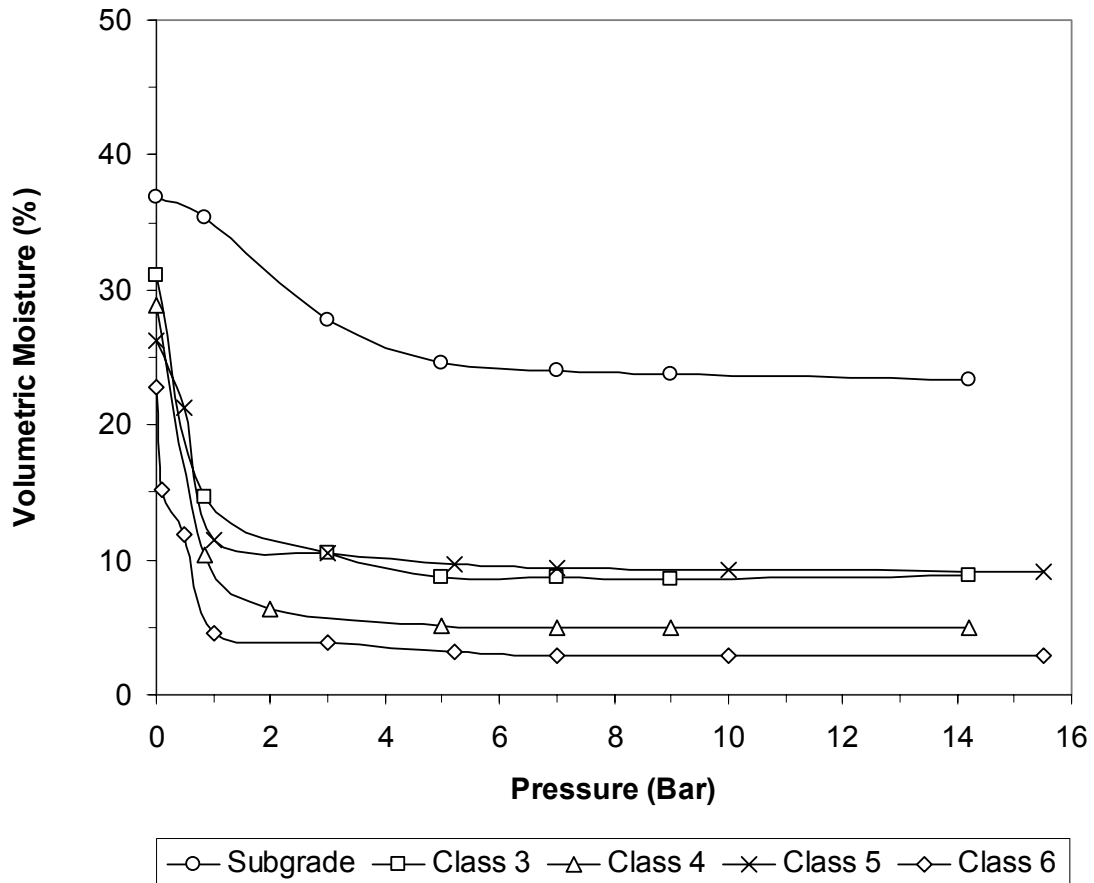


Fig. 2.2. Water retention of Mn/ROAD Subgrade, Subbase (Class 3 and Class 4), and Base (Class 5 and Class 6) materials.

Chapter 3. Development of a Theoretical Relationship Between Water Content and Apparent Dielectric Constant and Temperature

Development of the new composition-based calibration was based on a generic mixing equation, similar in form to a formula found in Tinga et al. (1973):

$$K_a = \sqrt[\alpha]{\theta K_{water}^\alpha + (1-\phi) K_{solids}^\alpha + (\phi-\theta) K_{air}^\alpha} \quad [1]$$

where K_a was the apparent dielectric constant of the bulk material. $K_{(water, solids, air)}$ were the apparent dielectric constants of water, solid particles, and air, respectively. θ = volumetric water content, ϕ = porosity of the solids, and α was a geometric factor accounting for spatial arrangements of the water, air, and solid materials.

Rearranging Eq. [1] by solving for water content, we obtained the following equation:

$$\theta = \frac{K_a^\alpha - (1-\phi) K_{solids}^\alpha - \phi K_{air}^\alpha}{K_{water}^\alpha - K_{air}^\alpha} \quad [2]$$

A majority of the Base, Subbase, and Subgrade solids are mineral materials and their dielectric constants have minimal temperature dependency (Drnevich et al., 2001). Furthermore, the dielectric constant of air is unity and not temperature dependent. Therefore, in Eq. [2], the effect of temperature can be expressed only in water content, apparent dielectric constant, and the dielectric constant of water:

$$\theta(T) = \frac{K_a^\alpha(T) - (1-\phi) K_{solids}^\alpha - \phi}{K_{water}^\alpha(T) - 1} \quad [2a]$$

Dielectric constant of the solids, K_{solids} , can be calculated as a weighted average of the mineral components: e.g., rock/sand/silt and clay. The dielectric constant of quartz is 4.2, so dry sand or rock fragments will have a dielectric constant of about 5.0. Depending on the type, the dielectric constant of clay ranges from 1.8 to 2.8. In this study, except the Subgrade that had about 20% clay, the Subbase and Base materials (sand and silt) had mostly mineral quartz materials.

The porosity (ϕ) of the solid material can be calculated from the bulk density (ρ_b) and mineral density (ρ_m) as follows

$$\phi = 1 - \frac{\rho_b}{\rho_m} \quad [3]$$

The average density of mineral materials is about 2.65 g/cm³.

The dielectric constant of water can be calculated, as a function of temperature, using the following equation found in Zegelin et al. (1992):

$$K_{water}(T) = 78.54 \left(1 - \frac{4.579(T-25)}{1000} + \frac{1.19(T-25)^2}{100000} - \frac{2.8(T-25)^3}{100000000} \right) \quad [4]$$

To summarize, the input parameters required for the new composition-based and temperature compensated calibration model are (i) apparent dielectric constant of the material, (ii) rock/sand/silt and clay fractions, (iii) bulk density, (iv) temperature, and (v) a geometric correction factor (α). The geometric correction factor (α) was determined empirically, for the Subgrade, Class 4 (representing the Subbase), Class 6 (representing the Base), and an agricultural soil, by fitting Eq. [2a] with measured values.

Chapter 4. TDR System Calibration: Dielectric Constant of Water as a Function of Temperature

To validate the TDR system, calibration was made using the laboratory tap water. For temperature settings below 15 °C, temperature control was achieved by mixing different ratios of ice and water in a 5-gallon bucket. Three thermocouples were placed in the bucket: one just below the water surface, one half-way to the bottom, and one near the bottom of the bucket to obtain an average water temperature and to determine the amount of ice to add in order to achieve the target temperatures (5, 10, and 15 °C). For temperature settings above 15 °C, temperature control was done by mixing different ratios of hot and cold tap water in the bucket. The final water temperatures ranged from about 5 to 45 °C which was representative of the temperature range in the pavement. The TDR probes used in the calibration were SoilMoisture® 20-cm 3-rod probes with 2-m leads. Although the probe configuration was different from the Mn/ROAD waveguides, this should not affect the experimental results because comparisons were based on the dielectric constant values. The theoretical relationship between the dielectric constant of water and temperature was calculated using Eq. [4] and compared to the measured values for each temperature settings (Fig. 4.1).

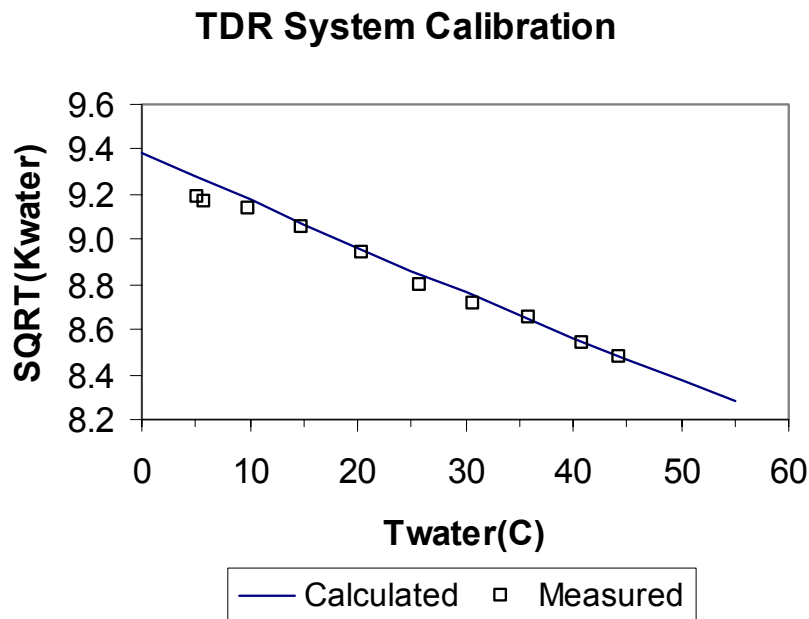


Figure 4.1 Dielectric Constant of Water as a Function of Temperature.

As shown in Fig. 4, the measured dielectric constant of water compared very closely with the calculated values. Near the 5 °C mark, however, the measurement was lower than the theoretical values. Because the low temperature was created by mixing cold tap water with ice and the TDR probes were suspended vertically in the bucket during the measurement, one explanation for the discrepancy at 5 °C was the existence of a temperature gradient along the waveguides in the bucket. To verify this, water

temperature was measured near the top and the bottom of the bucket during a gradual warming process from about 5 °C to room temperature (Fig. 4.2). The temperature measurement confirmed a temperature difference in the order of 0.5 °C between the top and the bottom of the bucket.

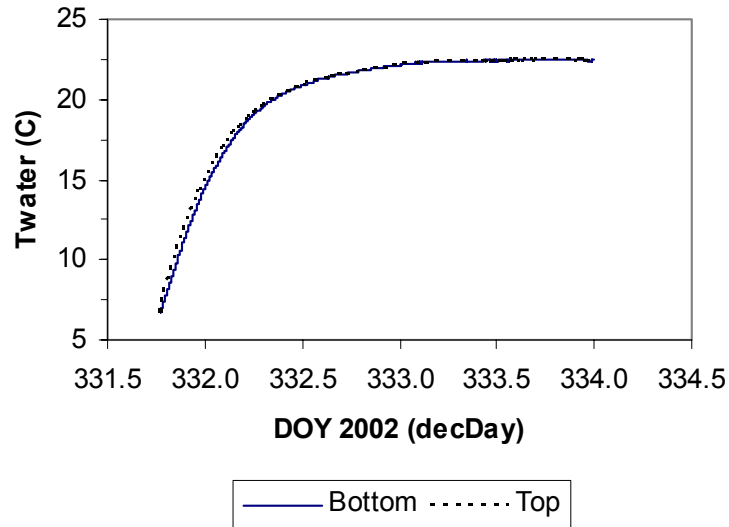


Figure 4.2 Water Temperature Near the Top and Bottom of a Bucket Used for TDR System Calibration.

Overall, the TDR system was reliable for producing the correct dielectric constant for water in the temperature range of 5 to 45 °C.

Chapter 5. Test Scenarios and Parameter Determination with Water Content as a Function of Dielectric Constant and Temperature

Based on the particle size and water retention information, the Subgrade, Class 4, and Class 6 were selected for the determination of water content as a function of dielectric constant and temperature. An agricultural soil was included as a reference because many TDR calibrations and applications were derived from agricultural soils. The agricultural soil was collected from a field site near Staples, MN. The field soil belongs to the Verndale sandy loam series (coarse loamy over sand, mixed, frigid, Udic Argiboroll). An environmental chamber was used to create temperature settings of 5 to 40 °C at a 5 °C increment. Four target water content values were used: 5, 10, 15 and 20 cm³/cm³ for each temperature setting.

An automated system consisted of a datalogger (CR10X from Campbell Scientific), a cable tester (TDR100 from Campbell Scientific), and the 3-rod SoilMoisture® TDR probes and thermocouple probes installed in each test sample was used in the data collection. Therefore, dielectric constant and temperature values during the transition between temperature settings were also collected.

As an example, comparisons of the square root of apparent dielectric constant (K_a) between 5% and 10% target water content as a function of temperature were shown for the four sample materials. Additional data is shown in Appendix A.

Subgrade Summary

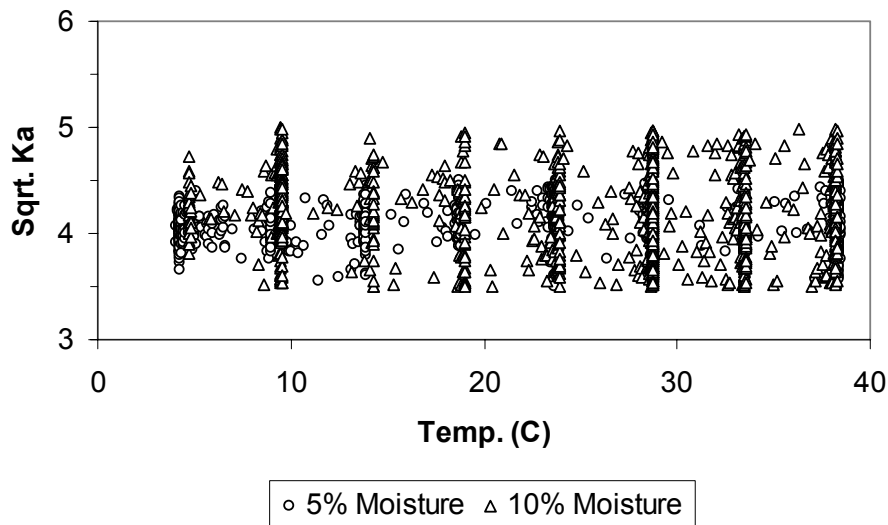


Figure 5.1. Comparison of Apparent Dielectric Constant (K_a) as a Function of Temperature.

Class 4 Summary

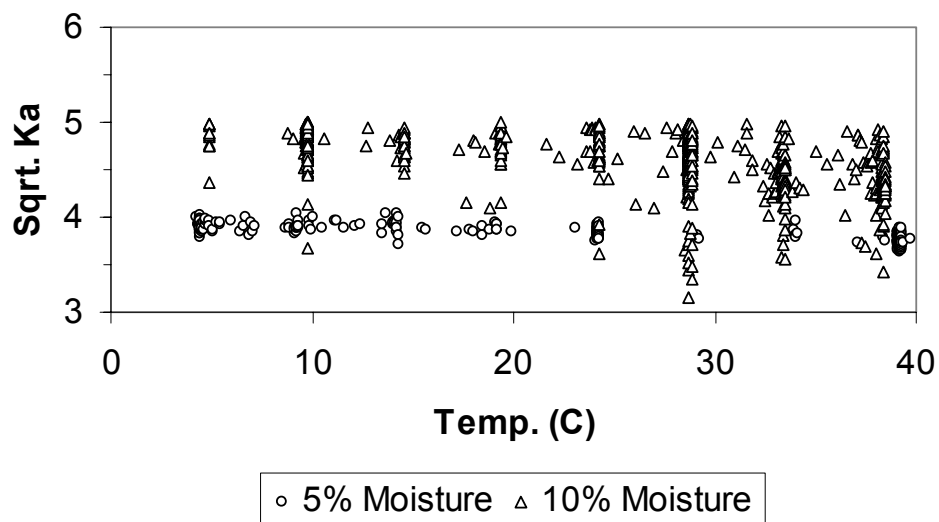


Figure 5.2. Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.

Class 6 Summary

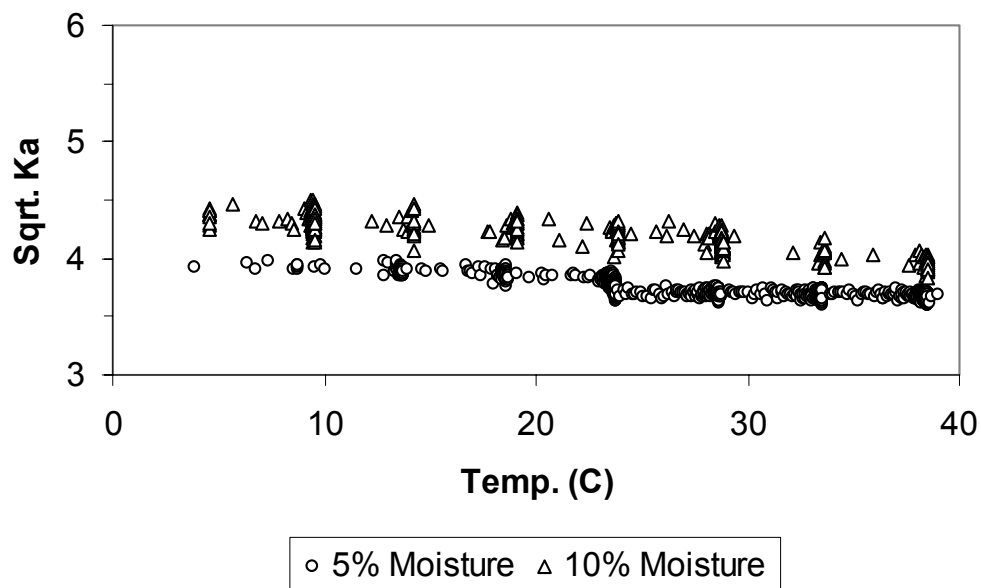


Figure 5.3. Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.

Staples Summary

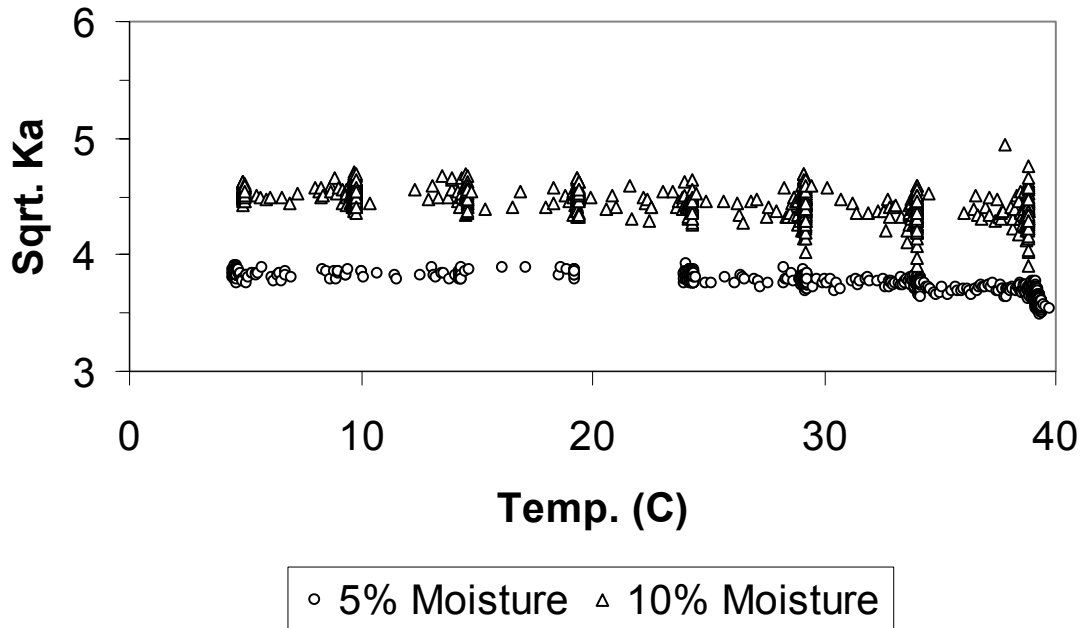


Figure 5.4 Comparison of Apparent Dielectric Constant (Ka) as a Function of Temperature.

The new composition-based and temperature compensated calibration model (equation [2a]) requires (i) apparent dielectric constant of the material, (ii) rock/sand/silt and clay fractions, (iii) porosity or bulk density, (iv) dielectric constant of water at a given temperature, and (v) a geometric correction factor (α). The geometric correction factor (α) was determined empirically by fitting equation [2a] with measured values. The results are summarized in Table 5.1.

Table 5.1. Test scenarios and Parameters for Determination of Water Content as a Function of Dielectric Constant and Temperature.

Soil	Target Water Content (%)	Actual Water Content (%)	Bulk Density (g/cm ³)	Porosity (-)	K_{solids}^{\dagger} (-)	α (-)	SE^{\S} (-)
Subgrade	5	3.4	1.67	0.37	4.37	2.3277	0.0103
	10	8.2	1.57	0.41	4.37	NC [‡]	
	15	13.1	1.46	0.45	4.37	NC	
	20	17.0	1.45	0.45	4.37	1.0504	0.0058
Class 4	5	1.4	1.87	0.29	5.00	2.5214	0.0031
	10	4.5	1.66	0.37	5.00	2.5389	0.0101
	15	14.2	1.84	0.31	5.00	NC	
	20	19.1	1.92	0.28	5.00	-0.0133	0.0054
Class 6	5	0.2	1.79	0.32	5.00	NC	
	10	4.6	1.74	0.34	5.00	2.0093	0.0028
	15	9.8	1.75	0.34	5.00	NC	
	20	14.1	1.59	0.40	5.00	0.3247	0.0035
Staples	5	1.1	1.64	0.38	5.00	NC	
	10	9.3	1.51	0.43	5.00	1.6684	0.0020
	15	12.2	1.66	0.37	5.00	1.7433	0.0091
	20	22.3	1.93	0.27	5.00	NC	

[†] Subgrade contained 21.4% clay, $K_{solids} = (78.6\% * 5.00) + ((21.4\% * 2.00)) = 4.37$
Class 4, 6, and Staples soil contained insignificant amount of clay, so $K_{solids} = (100\% * 5.00) + ((0\% * 2.00)) = 5.00$

[‡] NC represents no convergence.

[§] Standard error of the fitted geometric correction factor (α).

Chapter 6. Conclusions

A composition-based calibration equation (i.e. Eq. [2a]) was developed for predicting water content using apparent dielectric constant, temperature, texture composition, and a geometric correction factor as input variables. Whereas the apparent dielectric constant can be measured with TDR, the temperature with thermocouples, the texture composition may be determined with particle size and mineral analyses. In theory, the geometric correction factor should be conservative or relatively constant for a given texture if the particle arrangement was similar. The test results provided a somewhat confirmation such as in the Staples soil where $\alpha \sim 1.7$ (Table 1). In several instances, the model did not converge or the geometric factor was different when changing water content. The non-convergence and inconsistent α values were likely caused by the large scattering in the measured dielectric constant values, especially in the Subgrade material. Because of project limitations there was also no test made on the exact mineral composition of each textural class and no replication for the same water content-temperature-texture combinations. Therefore, data interpretation should be made with caution when applying the new calibration to make corrections in the Mn/ROAD dataset water content calculations. More rigorous testing is needed that will likely provide a more concrete validation of the new composition-based and temperature compensated calibration method for the pavement materials.

Chapter 7. Recommendations

The large scattering in the measured dielectric constant values in the Subgrade material, compared to the Base and Subbase, was attributed to the high clay content or large surface areas. As indicated in Logsdon (2000), in high-surface area porous media, a significant portion of the water will be tightly bounded. The bound water responds differently to TDR readings and to the temperature effect than the free water. This project did not explore the potential distinctions between the two types of water in the Subgrade or differentiate their responses to temperature changes. If TDR remains a major instrument for water content measurement in Mn/ROAD, we would recommend additional investigations to improve measurement reliability for the Subgrade and possibly incorporate new findings in the composition-based and temperature compensated calibration that has been developed in this project.

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APPENDIX A

Appendix A: Dielectric Constant of Mn/ROAD Materials as a Function of Temperature and Water Content (WC).

Appendix A: Dielectric Constant of Mn/ROAD Materials as a Function of Temperature and Water Content (WC).

