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Determination of Volumetric Moisture Content of Pavement Sublayers Using Time Domain Reflectometry Based on Micromechanics

Sang Ick Lee[1], Dan G. Zollinger[2], and Robert L. Lytton[3]

[1] Graduate Research Assistant, Texas A&M University, Zachry Department of Civil Engineering, 501H CE/TTI Building, College Station, TX 77843-3135; (O) 979-845-5982, (F) 979-845-0278; Email: s-lee@ttimail.tamu.edu

[2] Associate Professor, Texas A&M University, Zachry Department of Civil Engineering, 503E CE/TTI Building, College Station, TX 77843-3135; (O) 979-845-9918, (F) 979-845-0278; Email:d-zollinger@tamu.edu

[3] Professor, Texas A&M University, Zachry Department of Civil Engineering, 503A CE/TTI Building, College Station, TX 77843-3135; (O) 979-845-9964, (F) 979-845-0278; Email: r-lytton@civil.tamu.edu

Abstract

The moisture condition of pavement materials can significantly affect pavement performance. Although the importance of moisture content of sublayers has been well recognized, in-situ measurement and data collection had been difficult because of the limitations the measurement methods have. To understand the effect of climatic factors on moisture content, the Long Term Pavement Performance (LTPP) Seasonal Monitoring Program (SMP) was initiated for the measurement of in-situ moisture content of unbound base and subgrade materials using Time Domain Reflectometry (TDR) probes developed by the Federal Highway Administration (FHWA). However, the apparent length method presently used to determine the dielectric constant from a TDR trace is determined independent of other electrical properties of the conducting medium that may in some instants introduce a significant error. The empirical models for computing the volumetric water content used from LTPP SMP data does not consider the dielectric effect of the air in a soil mixture as well as the variation of dry density. These deficiencies basically create a significant systematic error in the final determination of volumetric water content. In order to minimize this error and improve the accuracy of the interpretation of the TDR data for calculating the volumetric moisture content, a new approach which consists of three steps is proposed. The approach employs the transmission line equation to calculate the dielectric constant, conductivity, and reflectivity of soil mixture. A micromechanics/self consistent scheme was used to determine the volumetric moisture content and dry density based on calibrated values of the soil and water dielectric constants. The systematic identification (SID) method was used iteratively to solve for dielectric parameters, soil moisture content, and density values. The validation of the new approach indicated that the calculated errors were less than 5% while those of existing method currently used are much higher.

Key Words dielectric constant, micromechanics, moisture content, self consistent scheme, system identification method, TDR, transmission line equation

Introduction

It is well known that the environmental factors, such as moisture content, temperature gradient, and depth of frost/thaw into the supporting materials, can have some effects on the structure design and performance of the pavement system. Especially, moisture in subbase layer can affect the response of the pavement to repetitive traffic loading. Although these factors have been an issue for many years, the relationship and amount of the effects have not well understood.

In order to understand the environmental factors and the relationship with pavement performance, the Seasonal Monitoring Program (SMP) was initiated within the Long Term Pavement Performance (LTPP) study in 1992. 64 LTPP test sections were selected for the SMP according to pavement type, thickness, environment, and subgrade type. Several instruments were installed at each section to acquire data on moisture content and temperature of sublayers, change in frost depth, and depth to ground water[1]. As part of this program, Time Domain Reflectometry (TDR) technology was selected to measure in-situ moisture content of pavement sublayers. TDR data was collected with 8-inch TDR probes developed by the Federal Highway Administration (FHWA). 10 TDR probes are placed at specified depths in different sublayer types and thicknesses below the outer wheel path[2].

In the LTPP SMP, the dielectric constant of soil is currently computed using the apparent length method from the TDR trace. The volumetric moisture content is empirically calculated using regression to relate the dielectric constant to the moisture content. However, these two methods can result in significant systematic errors because they are not able to fully consider the composite nature of the soil material.

In order to improve the accuracy of the interpretation of TDR data for calculating the volumetric moisture content, a new approach was developed. The approach employs the transmission line equation to calculate the dielectric constant, conductivity, and reflectivity of a soil mixture. A micromechanics/self consistent scheme was used to determine the volumetric moisture content and dry density based on calibrated values of the soil and water dielectric constants.

Estimation of Moisture Content in LTPP SMP

LTPP SMP determines the dielectric constant of soil based on the apparent length of TDR trace and calculates the moisture content using regression.

Determination of Apparent Length

An electromagnetic signal is transmitted along a TDR probe to determine the variation in voltage with distance along the probe. When the signal reaches the end of probe, it is reflected back to the device providing a means to record the voltage variation. The voltage variation manifests an initial inflection point (D_1) as the signal enters the probe rods and a final inflection point (D_2) is as the wave exits the end of the probes in the display of the TDR device. Ideally, the length between the inflection points should be the same as the length of TDR probe in a vacuum because of the lack of interference in the transmitted wave along a TDR probe. However, the velocity of wave is influenced by the dielectric constant of soil mixture surrounding the probe, so that as the velocity is delayed, the distance between inflection points increases.

The inflection points are determined using the method of tangents or the method of peaks that were found to be the most suitable methodology to determine the apparent length as was noted by Klemunes[3] shown in Fig. 1. The distance between the initial and final inflection points is the apparent length which is used to determine the dielectric constant of soil.

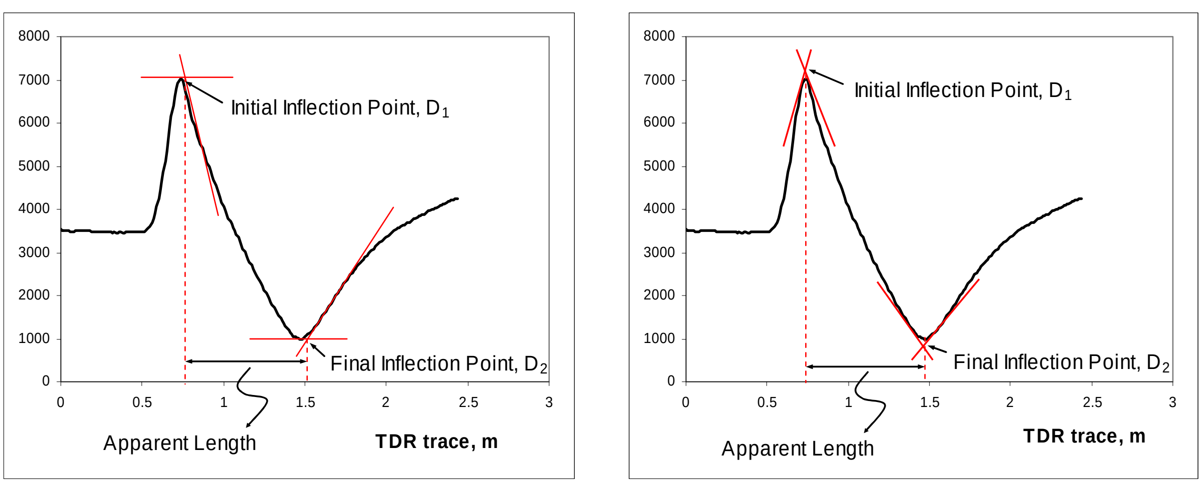
Computation of Dielectric Constant

The dielectric constant is derived from the relationship between the speed of light and the velocity of wave which is attenuated by dielectric properties of soil surrounding TDR probe. Since the dielectric constant of water is approximately 80 and that of dry soil is between 3 and 5, it can be concluded that the dielectric constant of soil mixture depends mainly on the moisture content. That is, because the dielectric constant of water is considerably larger than that of solid, the amount of water is a main factor in determining the dielectric constant for the soil-moisture-air mixture.

In the LTPP SMP, the dielectric constant determination includes a small adjustment for the phase velocity as follows[4]:

$$\varepsilon = \left(\frac{L_a}{L \cdot V_p} \right)^2 = \left(\frac{D_2 - D_1}{L \cdot V_p} \right)^2 \qquad (1)$$

where L_a = apparent length of TDR trace, m
L = actual length of TDR probe, 0.203 m (8 in) for FHWA probes, m
V_p = phase velocity setting on TDR cable tester (usually 0.99); this is the ratio of the actual propagation velocity to the speed of light.



(a) Method of Tangents (b) Method of Peaks

Fig. 1. Illustration of Trace Interpretation Methods [2]

Determination of In-situ Volumetric Moisture Content

The various methods[2] that have been proposed to determine soil volumetric moisture content have been mainly based on the empirical approaches which were developed using the regression functions with respect to the dielectric constant. LTPP SMP currently uses a 3rd order polynomial K_a and gradation regression model developed based on the dielectric constant (K_a) and intrinsic material properties that significantly affect the fine-grained soil[2].

The current methodology uses four empirical models for determining the volumetric moisture content based on the regressed relationship between the computed dielectric constant and the laboratory determined moisture content. The first three models actually represent non-plastic soil types with a the 3rd order polynomial and the fourth model is for plastic soils that manifest plastic liquid limits[2]. The models are selected based on the dielectric constant and ranges as shown in Fig. 2. The non-plastic models are broken into coarse-grained and fine-grained soil types to increase the accuracy of models, but the models can be used only within the specified dielectric constant range or the inference range. The equation for the non-plastic models is given below and the parameter of each model is shown in Table 1[2]:

$$\theta\ (\%) = a_0 + a_1\varepsilon + a_2\varepsilon^2 + a_3\varepsilon^3 \tag{2}$$

where ε = Dielectric constant in Table 1.
a_0, a_1, a_2, a_3 = Regression coefficients

In order to provide improved accuracy for plastic soil types, a separate model was developed based on intrinsic materials properties, such as gradation, plastic limit, and liquid limit. Again, this model can be used for fine-grained soils where dielectric constant and other parameters are within the inference region of the model noted in Table 2. The regression equation of this model is:

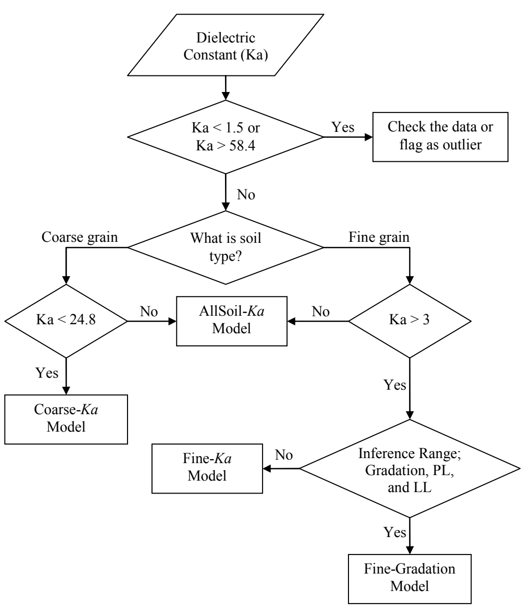


Fig. 2. Model Selection Process [2]

Table 1. 3rd Order Model Parameter Estimates[2]

Model	Coarse-K_a	Fine-K_a	AllSoil-K_a
a_0	-5.7875	0.4756	-0.8120
a_1	3.41763	2.75634	2.38682
a_2	-0.13117	-0.061667	-0.04427
a_3	0.00231	0.000476	0.000292

$$\theta(\%) = a_0 + a_1\varepsilon + a_2\varepsilon^2 + a_3\varepsilon^3 + a_4G11\_2 + a_5G1\_2 + a_6No4 + a_7No10 + a_8No200 + a_9PL + a_{10}LL \quad (3)$$

where θ = Volumetric moisture content
ε = Dielectric constant
$a_0, a_1, \ldots, a_{10}$ = Regression coefficients in Table 2

Table 2. Gradation Model Parameter Estimates[2]

Variable	Description	Coef.	Value	Inference Range
Intercept		a_0	1761.78	
K_a	Dielectric constant	a_1	2.9145	3 - 58.4
K_a^2		a_2	-0.07674	
K_a^3		a_3	0.000722	
G11_2	%passing 1½-sieve	a_4	-19.6649	99 - 100
G1_2	%passing ½-sieve	a_5	4.3667	97 - 100
No4	%passing No.4 sieve	a_6	-5.1516	90 - 100
No10	%passing No.10 sieve	a_7	2.7737	84 - 100
No200	%passing No.200 sieve	a_8	0.06057	12.6 - 94.6
PL	Plastic limit	a_9	-0.2057	0 - 45
LL	Liquid limit	a_{10}	0.10231	0 - 69

New Research Approach

The new approach suggested is unique in that the need for regression coefficients in the traditional sense is eliminated. That is, a micromechanics approach which accounts for the influence of the individual soil constituents is applied instead of a empirical approach in which no physical justification of the model from is considered[2]. Additionally, the determination of dielectric constant is carried out relative to other electrical properties of the conducting medium that if ignored, may introduce a significant error in the calculated dielectric constant.

In this research, in order to remove the error resulted from the empirical method, a new approach consisting of three steps was developed to estimate volumetric moisture content of pavement sublayers:

Step 1. Determination of dielectric constant from TDR trace
Step 2. Calibration of soil component dielectric constants using micromechanics/self-constant scheme
Step 3. Computation of volumetric moisture content and dry density

Determination of Dielectric Constant from TDR Trace

The approach currently used in LTPP SMP to determine the dielectric constant of soil is made to be independent of other electrical properties of the conducting medium influencing its value by assuming the soil magnetic permeability is unity. In this approach, the voltage trace is assumed to be a function of not only the dielectric constant but also the conductivity and the reflectivity. Considering these effects has inferred that the systematic error which otherwise results is significantly reduced.

Transmission Line Equation

The error occurred in the apparent length method can be reduce by using a model that more accurately reflects the actual physics of wave transmission through a dielectric medium. The transmission line equation accomplishes this through determining a conductivity and reflectivity of surrounding medium as well as the dielectric constant. The general solution for the voltage V(z) on the transmission line is[5]:

$$\mathrm{V(z)} = \mathrm{V}_{+} e^{-jkz} + \mathrm{V}_{-} e^{+jkz} \tag{4}$$

where V = applied voltage
z = distance along the line (m)
V_+ = amplitude traveling in the positive direction
V- = amplitude traveling in the negative direction
k = dispersion coefficient (= $k_R - jk_I$, real and imaginary components)

Equation 4 can be developed as:

$$\mathrm{V(z)} = \mathrm{V}_{+} (e^{-jkz} + \Gamma_L e^{+jkz}) \tag{5}$$

because the reflection coefficient, Γ_L, is:

$$\Gamma_L = \frac{\mathrm{V}_{-}}{\mathrm{V}_{+}} \tag{6}$$

To calculate the relative voltage in terms of time travel of the microwave, Equation 5 is arranged as[5]

$$\mathrm{V}(t) = \left(e^{-\frac{\sigma t}{2\varepsilon\sqrt{\varepsilon_0}}} + \Gamma_L e^{+\frac{\sigma t}{2\varepsilon\sqrt{\varepsilon_0}}} \right) \cdot \cos\left(\omega \frac{t}{\sqrt{\varepsilon_0}} \right) \tag{7}$$

where σ = soil conductivity (S/m)
t = time (sec)
ε_0 = electric permittivity of free space = $\frac{1}{36\pi} \times 10^{-9}$ F/m

ε = dielectric constant of the soil
Γ_L = reflection coefficient
ω = angular frequency (Hz)

The relative voltage and time are of course obtained directly from a TDR trace, but the dielectric constant, conductivity, and reflection coefficient are unknown values; their determination is facilitated by use of the system identification (SID) method.

System Identification Method

The System Identification (SID) method is an iterative solution scheme that can be used to minimize the error between the system output and the model output based on the same input signal by adjustment of the variable unknowns[6]. The output of the model is changed systematically using a search technique until the model output is closed to the system output[7]. In the new approach, the SID was used to fit the transmission line equation for relative voltage to the form of the TDR trace by the iteration process until ΔX_i^n (the difference in the unknown parameter from iteration to iteration) equals zero by satisfying the following expression for each point selected from the TDR trace:

$$\sum_{1}^{n=m}\left(\frac{\partial v(t)_i}{\partial X_i}\frac{X_i^n}{v(t)_i^n}\right)\left(\frac{\Delta X_i^n}{X_i^n}\right)=\frac{\Delta v(t)_i^n}{v(t)_i^n} \qquad (8)$$

where m = number of X_i^n which are determined for measured value (in this case = 3)
X_i^n = dielectric constant (e), conductivity (s), reflectivity (Γ)
ΔX_i^n = $X_i^{n+1} - X_i^n$
n = iteration count
$\Delta v(t)_i^n$ = $v_c(t)_i^n - v_m(t)_i^n$
$v_c(t)_i^n$ = calculated value based on the current values of X_i^n using transmission line equation
$v_m(t)_i^n$ = measured value from TDR trace

For each of the unknowns above, matrix analysis can be utilized to solve the set of resulting equations for each set of data points taken from the TDR trace as:

$$[F]\{\beta\}=[\underline{r}] \qquad (9)$$

where $[F]$ = matrix of $\frac{\partial v(z)_i}{\partial X_i}\frac{X_i^n}{v(z)_i^n}$ elements (sensitivity matrix)

$\{\beta\}$ = matrix of $\frac{\Delta X_i^n}{X_i^n}$ elements (unknown gradient matrix)

$[\underline{r}]$ = matrix of $\frac{\Delta v(z)_i^n}{v(z)_i^n}$ elements (residual matrix)

The number of recorded data points from the TDR trace determines the number of rows in matrices $[F]$ and $[\underline{r}]$, while the number of columns in matrix $[F]$ and the number of rows in matrix $[\beta]$ are the same as the number of unknown parameters to be calculated. The matrix equation 12 can be solved as:

$$\{\beta\} = \left[F^T F\right]^{-1} \left[F^T\right] \left[\underline{r}\right] \qquad (10)$$

By minimizing the residual matrix $\{\beta\}$, solutions for X_i^n (i.e. conductivity (σ), dielectric constant (ε), and the reflection coefficient (Γ)) are found. The minimization of error contained within the residual matrix $[\underline{r}]$ is analogous to the minimization or reduction of error employed least squared error analysis. In this approach, when each element of the matrix $\{\beta\}$ is less than 0.01 by using the iteration process, then it was considered that the parameters were found. Fig. 3 shows the solution and iteration process to find the parameters, but even though the new approach employs regression analysis, no regression coefficients result.

Calibration of Soil Component Dielectrics using Micromechanics/Self-constant Scheme

The new method used to determine the dielectric constant and moisture content does consider soil components: soil, solid, and water. This more fundamental approach which regards soil as a composite material can account for the effect of individual constituent soil dielectrics on the moisture content. In this regard, a theory of dielectric properties of composite materials from micromechanics/self consistent scheme yields a general expression for a 2-phase composite dielectric constant[8]:

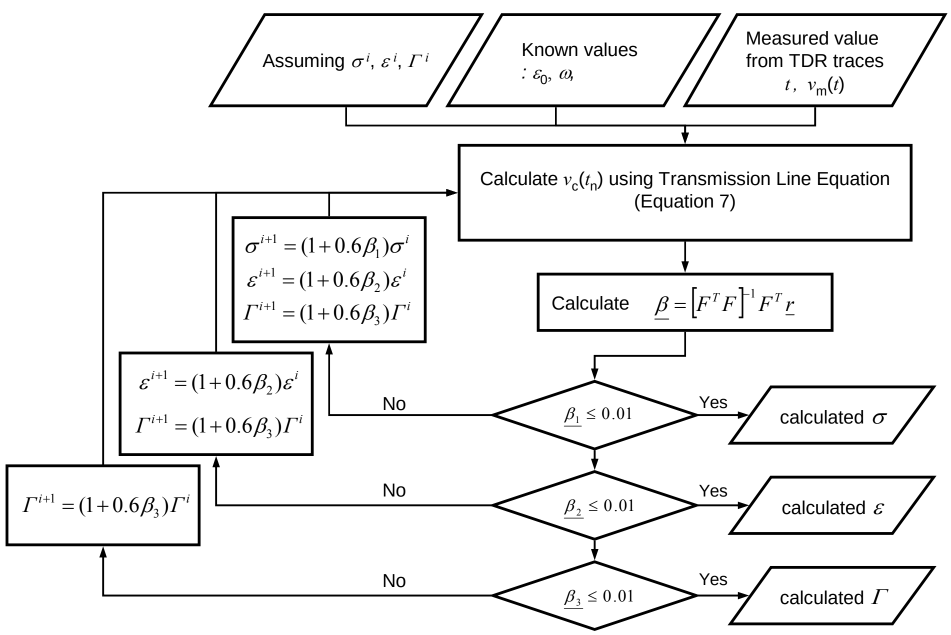


Fig. 3. Determination of Dielectric Constant Using SID

$$v_1\left[\frac{\varepsilon_1-\varepsilon}{\varepsilon_1+2\varepsilon}\right]+v_2\left[\frac{\varepsilon_2-\varepsilon}{\varepsilon_2+2\varepsilon}\right]=0 \tag{11}$$

where ε_1 = dielectric constant for phase 1
ε_2 = dielectric constant for phase 2
ε = composite dielectric constant
v_1 = volume fraction of phase 1
v_2 = volume fraction of phase 2

The justification for a self consistent scheme lies in the volume fractional boundary in which the computed volumetric moisture contents falls. In other words, the computed moisture contents are consistent with bounded values of dielectric constants of the individual phases and their volume fractions as shown in Fig. 5. The upper (+) and lower (–) dielectric expressions are[8]:

$$\varepsilon_- = \varepsilon_1 + \frac{v_2}{\dfrac{1}{\varepsilon_2-\varepsilon_1}-\dfrac{v_1}{2\varepsilon_1}},$$

$$\varepsilon_+ = \varepsilon_2 + \frac{v_1}{\dfrac{1}{\varepsilon_2-\varepsilon_1}-\dfrac{v_2}{2\varepsilon_2}}$$

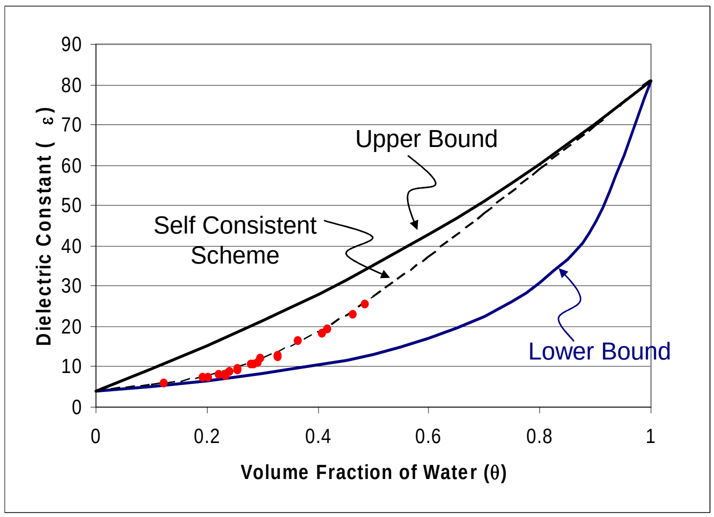


Fig. 4. Bounds of Dielectric Constant as a Function of the Computed Volumetric Moisture Content[8]

Using this concept, an expression can be written for a 3-phase system (air-water-solids mixture) based on Equation 11:

$$\frac{\gamma_d}{G_s\gamma_w}\cdot\frac{\varepsilon_1-\varepsilon}{\varepsilon_1+2\varepsilon}+\theta\cdot\frac{\varepsilon_2-\varepsilon}{\varepsilon_2+2\varepsilon}+\left(1-\frac{\gamma_d}{G_s\gamma_w}-\theta\right)\frac{\varepsilon_3-\varepsilon}{\varepsilon_3+2\varepsilon}=0 \tag{12}$$

where γ_d = dry density of soil (g/cm^3)
Gs = specific gravity of soil
γ_w = unit weight of water (g/cm^3)
ε_1 = dielectric constant of solids
ε_2 = dielectric constant of water
ε_3 = dielectric constant of air (= 1.0)
ε = dielectric constant of the soil determined from step 1
θ = volumetric moisture content (%)

With a value for ε determined from a TDR trace, the values of ε_1, ε_2, and G_s of the model are adjusted and calibrated based on the ground truth data of measured values of γ_d and θ using the SID approach used in the previous step. The calibrated values can be further used to calculate volumetric moisture content and dry density.

Computation of Volumetric Moisture Content and Dry Density

In addition to the error associated with the apparent length method previously noted, another perhaps less systematic error results from assuming the dry density of soil is unvarying. Since the empirical methods currently used are based on the assumption that the calculated volumetric moisture content is based upon a constant dry density. This type error can be removed by considering the dielectric effect of the air in the soil and calculating the dry density of soil every time the moisture content is estimated.

Step 3 is for the computation of volumetric moisture content and dry density based on a similar use of the SID method and the calibrated constants. Once a particular soil's characteristics, ε_1, ε_2, and G_s, are identified by Step 2, all future calculations of γ_d and θ can be determined by use of the SID using of course a different soil dielectric constant determined from the analysis described in Step 1. In this manner, the calibrated constants ε_1, ε_2, and G_s are used to compute the new value of γ_d and θ using the micromechanics/self consistent model noted as Equation 12.

Validation

As part of an effort to validate the new approach described in this paper, comparisons were made to the computed moisture content from the 3rd order polynomial K_a and gradation model and to laboratory determined moisture contents from the representative LTPP SMP site soil samples. This validation consisted of matching in-situ soil samples and their moisture contents to the corresponding TDR location. Laboratory test data was based on soil samples taken from 4 representatives of 28 possible LTPP SMP sections obtained from Klemunes' thesis work[3] where he varied the moisture content and soil density with matching TDR traces.

The 4 representative data were selected to represent a range of soil types which were gravel, sand, silt, and clay. For each section, one installation TDR trace and corresponding moisture content were used to calibrate the micromechanics model. Calibration information relative to the soil and water dielectric constants can be found in Table 3. Using the calibrated information and the TDR traces obtained at different moisture contents, the estimates of moisture content and dry densities were computed as shown in Table 4 along with estimates from the empirical model and the laboratory test results. Fig. 5 indicates the associated difference of each method for each trial. The micromechanics method resulted in smaller amounts of difference as compared to the empirical method. This was the case for all trials except section 231026-B which resulted in approximately equivalent differences for both methods, which is not unexpected since a sandy material is involved.

Table 3. Calibration of Dielectric Constants by Transmission Line Equation.

Section	Soil Type	Spec. Gravity	Dry Density (g/cm^3)	Dielectric Constant		Volumetric Moisture Content (%)
				Soil (α_1)	Water (α_2)	
271028	Gravel	2.724	2.017	3.79	80.6	7.06
231026	Sand	2.782	1.960	3.79	80.0	19.35
091803	Silt	2.864	2.264	3.89	81.0	20.38
081053	Clay	2.890	1.634	3.79	80.0	21.57

Table 4. Comparison of Moisture Contents.

Section		Soil Type	Dry Density (g/cm^3)		Volumetric Moisture Contents (%)			
			Lab.	M.M.*	Ground Truth (Lab Result)	Empirical Method (3rd Polynomial Equation)		Micromechanics Method
271028	C	Gravel	1.730	1.810	7.09	9.36	Coarse-K_a	7.79
	F		1.712	1.700	12.50	13.92	Coarse-K_a	12.17
	K		1.766	1.869	18.98	20.06	Coarse-K_a	19.78
231026	B	Sand	1.574	1.558	14.88	15.40	Coarse-K_a	14.25
	F		1.635	1.610	22.98	21.78	Coarse-K_a	21.95
	M		1.605	1.569	7.54	8.34	Coarse-K_a	7.18
091803	C	Silt	0.976	0.989	38.45	29.63	Fine-K_a	38.05
	I		0.965	0.924	27.12	21.01	Fine-K_a	28.07
	P		0.965	0.927	29.65	20.48	Fine-K_a	28.94
	W		0.973	0.923	39.30	32.35	Fine-K_a	38.16
081053	G	Clay	1.406	1.350	44.07	51.80	Fine-Gradation	44.81
	K		1.40	1.321	48.83	51.80	Fine-Gradation	48.03
	U		1.377	1.440	30.72	29.67	Fine-Gradation	31.29

* Micromechanics method

The evaluation of estimated dry densities was performed by comparison to measured values obtained the from the laboratory test. Fig. 6 shows higher capabilities and accuracy of the micromechanics model in estimating dry density with differences less than 6 percent.

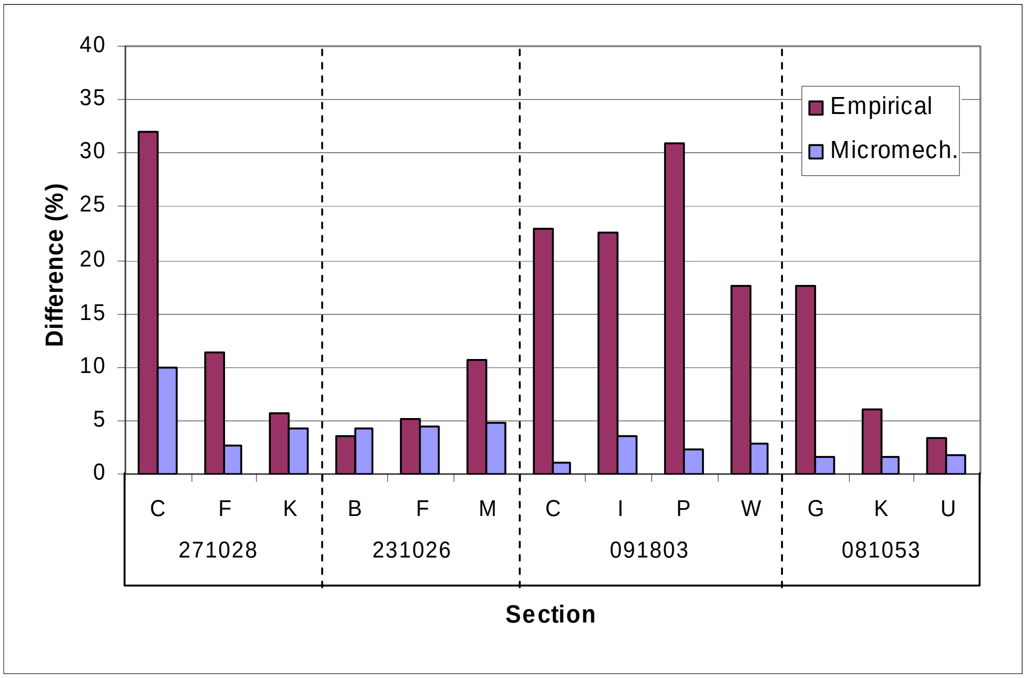


Fig. 5. Differences of Volumetric Moisture Contents on Ground Truth Data

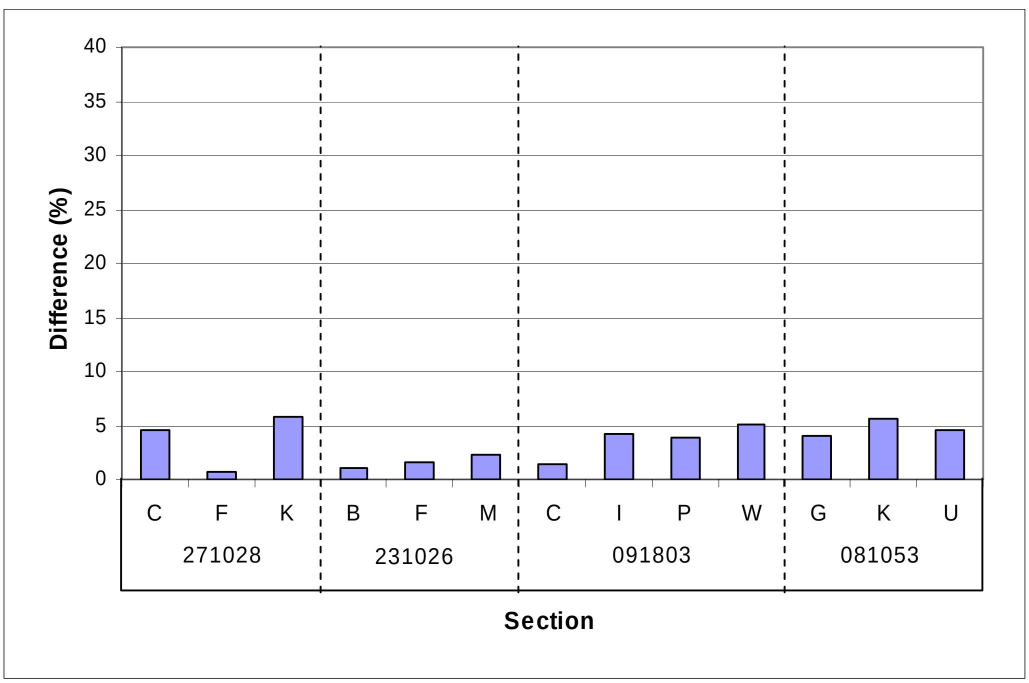


Fig. 6. Differences Between Estimated Dry Density and Ground Truth Data

The moisture content determined using the new approach has significantly less error when compared to laboratory test results than the empirical method does.

Conclusions

Since a TDR trace provides a nondestructive in-situ measurement of the composite nature of an in-situ material, the moisture content of pavement sublayers can be estimated by a suitable analysis of the trace. However, the apparent length method to determine the dielectric constant fails to consider soil conductivity and reflectivity influences on the dielectric value. The empirical method currently used to estimate the volumetric moisture also does not consider the dielectric effect of the air in soil and the change of dry density. These limitations work together to cause potential systematic errors in the accuracy of the resulting moisture estimates.

In order to minimize the systematic errors occurred from existing methods, a new approach, applying the transmission line equation and a 3-phase micromechanics model consisting of three steps, was developed:

Step 1. Calculate the dielectric constant, conductivity, and reflectivity from a TDR trace using the transmission line equation and the SID method.

Step 2. With ground truth moisture content and dry density data along with the dielectric constant calculated from step 1, calibrate the dielectric constant of the soil and water and the specific gravity of soil. The SID and the following three phase micromechanics model are utilized for the calibration:

$$\frac{\gamma_d}{G_s\gamma_w}\cdot\frac{\varepsilon_1-\varepsilon}{\varepsilon_1+2\varepsilon}+\theta\cdot\frac{\varepsilon_2-\varepsilon}{\varepsilon_2+2\varepsilon}+\left(1-\frac{\gamma_d}{G_s\gamma_w}-\theta\right)\frac{\varepsilon_3-\varepsilon}{\varepsilon_3+2\varepsilon}=0$$

Step 3. With the calibrated step 2 values, forward calculate, using the SID method, the volumetric water content and dry density of the soil for the TDR traces obtained at other times and the associated dielectric constant determined from Step 1.

The validation of this new approach with ground truth data obtained from laboratory evaluation indicated that the percent error of the micromechanics method are less than 5 % while those of existing methods currently used are much higher. Also, the dry density determined using micromechanics method has significantly less error when compared to the laboratory test result.

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Biographical Information

Sang Ick Lee completed his B.S. and M.S. in Civil Engineering at the Chung-Ang Univerisy in South Korea. He currently is working towards the Ph.D. degree in Zachry Department of Civil Engineering at the Texas A&M University in College Station, Texas.

Dan G. Zollinger obtained his B.S. and M.S. degrees in Civil Engineering at the Utah State University and his Ph.D. degree from the University of Illinois at Urbana-Champaign. He is an Associate professor in Zachry Department of Civil Engineering at Texas A&M University and is an Associate Research Engineer at the Texas Transportation Institute.

Robert L. Lytton obtained his B.S., M.S., and Ph.D. degrees in Civil Engineering at the University of Texas at Austin. He is the Fred J. Benson Chair Professor in Zachry Department of Civil Engineering at Texas A&M University and is a Research Engineer at the Texas Transportation Institute.