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Improving TDR Measurements through Accounting for Soil Shrinkage Properties

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Abstract. *Time domain reflectometry (TDR) is a widely used tool for indirect measurement of soil moisture content. Empirical formulation is used to link the apparent dielectric constant of soil to the volumetric moisture content (Topp's Equation: Topp et al., 1980) or gravimetric moisture content as a function of soil bulk density (Siddiqui and Drnevich Equation: Siddiqui and Drnevich, 1995). This paper introduces a methodology to account for soil volume change by integrating the true bulk* *density of the soil into the measurements using the soil Shrinkage Curve (specific volume (cm^3/g) versus gravimetric water content). Thus, bulk density becomes a non-constant parameter that can be calculated as a function of the soil water content in the Siddiqui and Drnevich Equation. Experimental evidence demonstrates accounting for soil shrinkage improves the accuracy of TDR measured moisture contents and allows for estimating the shrinkage curve. Direct water content calculation for the Chalmers soil was compared to water contents from TDR readings* with *and* without *shrinkage corrections; those with shrinkage corrections showed significantly improved accuracy in TDR-determined soil moisture.*

Keywords. TDR, soil structure, shrinkage properties, shrinkage curve, drying process, water content.

Introduction

Achieving accurate measurements of the soil moisture content is an active area of research and experimentation (Noborio, 2001, Evett and Parkin, 2005, Robinson et al., 2003 and 2008). Various direct and indirect methods for the measurement and estimation of the water content have been developed including oven-drying, as well as the in-situ electrical resistance, neutron probe, tensiometers, and time domain reflectometry (TDR). While the oven-drying method represents the only direct method for the measurement of soil water content, non-destructive in-situ measurements require empirical or constitutive correlations between water content and soil response to certain sensor stimuli like change in concentration of slowed neutrons, electrical conductivity, or the soil apparent dielectric constant, K_a.

TDR, a widely accepted and increasingly accurate measurement method of soil water content, relies on the accurate measurement of K_a given its sensitivity to the amount of water in the soil (Topp et al., 1980, Siddiqui et al., 2000, Drnevich et al., 2005, Yu and Drnevich, 2004). This sensitivity comes from the large difference between K_a for water (around 81), soil particles (between 2 and 7) and air (around 1) (Drnevich et al., 2005). Most TDR equipment uses the Topp equation (Equation 1: Topp et al., 1980) in the estimation of the volumetric water content using a cubic equation in terms of K_a. Siddiqui and Drnevich (1995) derived a relationship between K_a, dry bulk density (ρ_d), and the gravimetric water content of the soil, w (Equation 2):

$$\theta_{TDR} = -5.3\times10^{-2} + 2.92\times10^{-2} k_a - 5.5\times10^{-4} k_a^2 + 4.3\times10^{-6} k_a^3 \qquad \text{Equation 1}$$

$$\sqrt{K_a}\,\frac{\rho_w}{\rho_d} = a + bw \qquad \text{Equation 2}$$

where ρ_w is the density of water. a and b are soil-dependent parameters with a related to ρ_d and the K_a of the dry soil and b related to the increase K_a with increase in the pore fluid.

While the effect of ρ_d on the Siddiqui and Drnevich Equation has been studied in the context of compaction energy due to its direct relevance to geotechnical applications (Drnevich et al., 2005), the effect of change in ρ_d due the soil shrinkage has not been addressed yet. Accordingly, the effect of structural interaction and internal stress (or energy) change due to shrinkage on K_a and TDR response is not fully understood. Moreover, various studies on clayey and silty soils have observed considerable effect for temperature, clay content, salinity, saturating cations, frequency, pH, and CEC on the water content predictability using K_a through empirical formulation (Saarenketo, 1998, Ponizovsky et al., 1999, Ishida and Makino, 1999, Logsdon and Laird, 2004, Kelleners et al., 2004, Chen and Or, 2006, Robinson et al., 2008). Such observations call for more physically based understanding of the relationship between K_a and water content.

This paper assesses the performance of the Topp's as well as the Siddiqui and Drnevich Equations in predicting the volumetric and gravimetric water contents of a drying silty clay loam soil. The paper then introduces a methodology to account for the soil hydro-structural change effect by introducing the real soil specific volume, $1/\rho_d$, as a function of the gravimetric water content, w, (obtained from the soil Shrinkage Curve) into Equation 2 that is used for the measurement of w. Thus, bulk density becomes a non-constant parameter that can be calculated as a function of the soil water content using the experimental procedure defined in Braudeau *et al.*, 1999. Finally, the paper presents a new methodology to reconstruct/estimate the shrinkage curve using only five data points to calibrate the TDR estimates of gravimetric and volumetric water contents. The new methodology is tested by calibrating the TDR with data from a soil sample and then using the calibration parameters to reconstruct the shrinkage curve (of another experiment) with a very close fit.

Materials and Methods

To assess the effect of soil volume change due to shrinkage, continuous measurements of volumetric water content as estimated by the TDR (θ_{TDR}) must be compared with simultaneous and direct measurement of the real gravimetric water content w_{Real}, as well as simultaneous calculation of $1/\rho_d$, taking into account the relationship between gravimetric (w) and volumetric (θ) water contents (Equation 3). This becomes an ideal setup for a typical shrinkage curve experiment (Braudeau *et al.*, 1999, Braudeau *et al.*, 2004) with the addition of the TDR probe and equipment.

$$w = \theta \frac{\rho_w}{\rho_d} \qquad \text{Equation 3}$$

Accordingly, comparisons can be made between the measured (w_{Real}) and predicted gravimetric water content (w_{TDR}), derived from θ_{TDR} using Equation 3 and results of ρ_d from the shrinkage curve. Similarly, comparisons can be made between the measured volumetric water content (θ_{Real}), (derived from w_{Real} using Equation 3 and results of ρ_d from the shrinkage curve) and predicted θ_{TDR}. The effect of change in ρ_d due to shrinkage on the TDR methodology for measuring the soil water content, can be assessed by comparing the performance of TDR equipment using: (1) built-in parameters vs. soil-specific parameters, (2) a single value of ρ_d and (3) the specific volume, $1/\rho_d$, as function of w_{Real} (according to the Shrinkage Curve).

Procedure

The procedure followed in the experiments (Figure 1) was:

1. **Soil preparation:** Disturbed soil was sieved using sieve #4 and mixed with water to the desired water content (near saturation). The soil mixture was sealed and kept for a week in humid room to allow the water content to equilibrate.
2. **Specimen base:** An acrylic sheet, randomly perforated (with 3/16-inch (4.7-mm) diameter holes) was used as the base for the soil specimen. The sheet was overlaid with randomly-cut small geotextile sheets (Figure 1) to allow for water exfiltration or evaporation from the bottom of the specimen while preventing the loss of soil as water escapes the soil.
3. **Sample preparation:** The soil specimen was prepared by uniformly compacting soil in multiple layers (6 to 8) inside a PVC tube (15cm long and 7.73cm in diameter), used only to confine the soil. A thin layer of oil was placed on the inside of the PVC tube to reduce the friction between the PVC and the soil.
4. **TDR Equipment:** A TRASE TDR unit (SoilMoisture Equipment Corp) was used in these experiments. The TDR three-rod probe provided with the TRASE TDR was inserted into the soil specimen and the TDR equipment built-in software was used to collect K_a and θ_{TDR} readings every 10 minutes for the test duration which lasted approximately four weeks.
5. **Calculation of w_{Real}:** The soil specimen was placed on an electronic balance connected to a data acquisition system (using WinWedge software) and the data acquisition system

was programmed to measure the mass of the soil specimen at 10 minute intervals. At the end of the experiment, the gravimetric water content of the specimen was determined by oven drying. Using the last gravimetric water content as a starting point, the water contents of the soil specimen was back calculated as a function of time by use of the measured specimen mass.

6. **Calculation of ρ_d:** The change in specimen length due to shrinkage was measure by using an LVDT. Assuming isotropic shrinkage of the specimen (Braudeau *et al.*, 1999, Braudeau *et al.*, 2004), and using the soil mass obtained from the previous step, the bulk density (or specific volume) can be calculated as function of time. To avoid any punching effect by the LVDT core, the core was placed on a geotextile sheet instead of directly being placed on the soil.

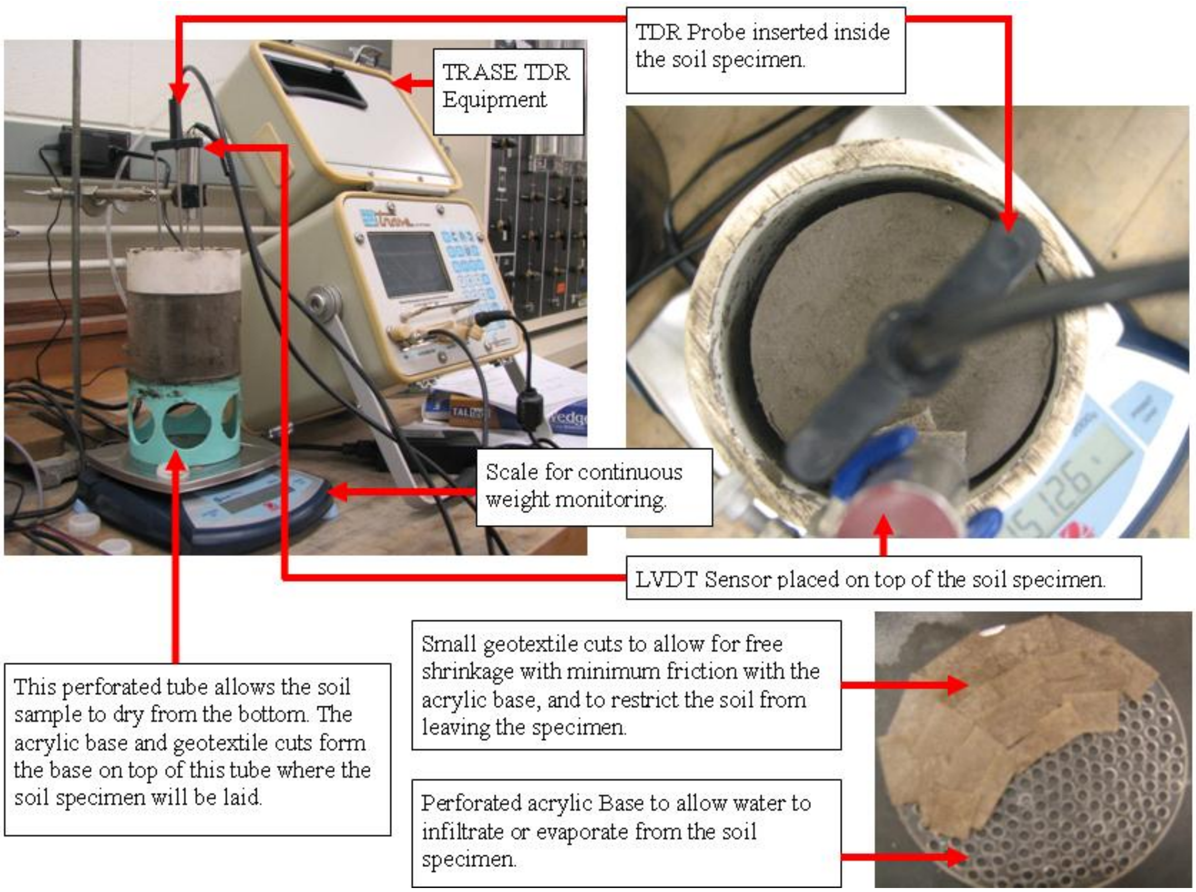

Figure 1. Schematic of the experiment procedure.

It was a challenge to minimize the water content gradients in the soil specimen because those gradients could affect the TDR readings. This objective was partially achieved by allowing the soil specimen to dry at room temperature from the top, bottom, and side boundaries (as the soil shrinks, the soil loses contact with the PVC tube). The design of the soil specimen base and the use of oil at the PVC tube allowed for drying from the bottom and boundaries, respectively.

In nutshell, the shrinkage curve experimental setup is used as a control for the purpose of this study providing w_{Real} and ρ_d as function of time. The TDR equipment on the other hand provides

θ_{TDR} (volumetric water content estimated by the TDR) and K_a. The objective of this study is assess the accuracy of θ_{TDR} (and the w_{TDR} derived there from) as provided by the TDR equipment to improve those values over those by solving for soil-specific constants (Equations 1 and 2) using a single value of ρ_d ($w_{TDR\_Single\ \rho d}$), through solving for soil-specific constants using instantaneous values of ρ_d as predicted and measured by the shrinkage curve (w_{TDR_ShC}).

Materials

Samples of the Chalmers clay loam soil were collected from the Agronomy Center for Research and Education (ACRE) at Purdue University. The Chalmers soil consists of 15% sand, 45% silt, and 40% clay. A complete list of soil properties is provided by Abou Najm et al. (2008). The use of disturbed samples (as explained in the previous section) instead of undisturbed field-collected specimens was favored since laboratory-made soil specimens can be prepared with more uniformity, thus avoiding the presence of large stones, non-soil residues, and major cracks and discontinuities.

Experimental Results

Three experiments were conducted for the same soil following the procedure explained in the previous section. The average duration of each experiment was around 27 days. At the end of each experiment, data was downloaded and analyzed to obtain: θ_{TDR} and K_a (from the TDR unit), w_{Real} (from electronic balance), and ρ_d (from electronic balance and LVDT). w_{TDR} and θ_{Real} were then derived using θ_{TDR}, w_{Real}, ρ_d and Equation 3. Figure 2 shows the shrinkage curve of the Chalmers soil from the first experiment (*experiment 1*). The shrinkage curve is presented in specific volume, $1/\rho_d$ (cm^3/g), as function of w.

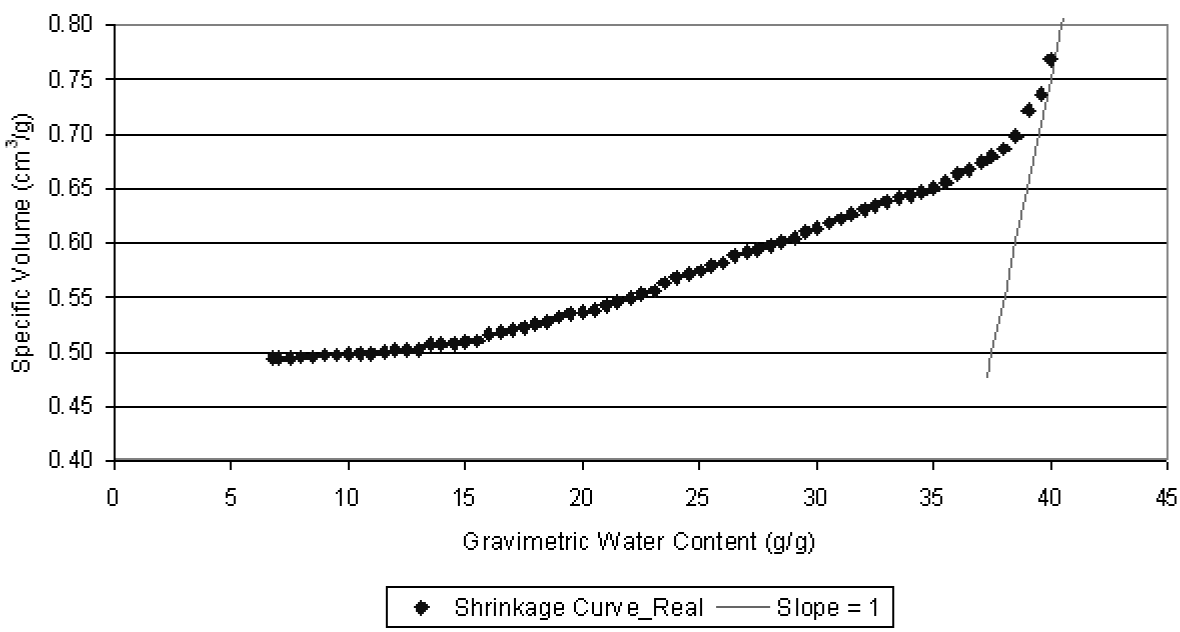

Figure 2. The shrinkage curve of the Chalmers Soil from *experiment 1*.

Comparison with Topp's Equation

Figure 3 shows a comparison between the non-calibrated TDR readings (θ_{TDR} and w_{TDR}: using Topp's Equation) and the real gravimetric (w_{Real}) and volumetric (θ_{Real}) water contents for *experiment 1* as obtained by the shrinkage curve. It is clear from Figure 3 that the TDR predictions (θ_{TDR} and w_{TDR}) were not very representative of the real water content of the soil specimen (θ_{Real} and w_{Real}). The main reasons behind the differences in the water contents are: (1) the relatively high clay content of the soil causing dielectric dispersion or change in permittivity as function of frequency (Saarenketo, 1998, Ishida and Makino, 1999, Chen and Or, 2006, Robinson et al., 2008), (2) the high shrinkage range of the soil (ρ_d increased from around 1.30 g/cm^3 to 2.0 g/cm^{3}as the soil dried from w_{Real}=40.01% to w_{Real}=6.75%), and (3) the empirical nature of the Topp's equation (Topp et al., 1980).

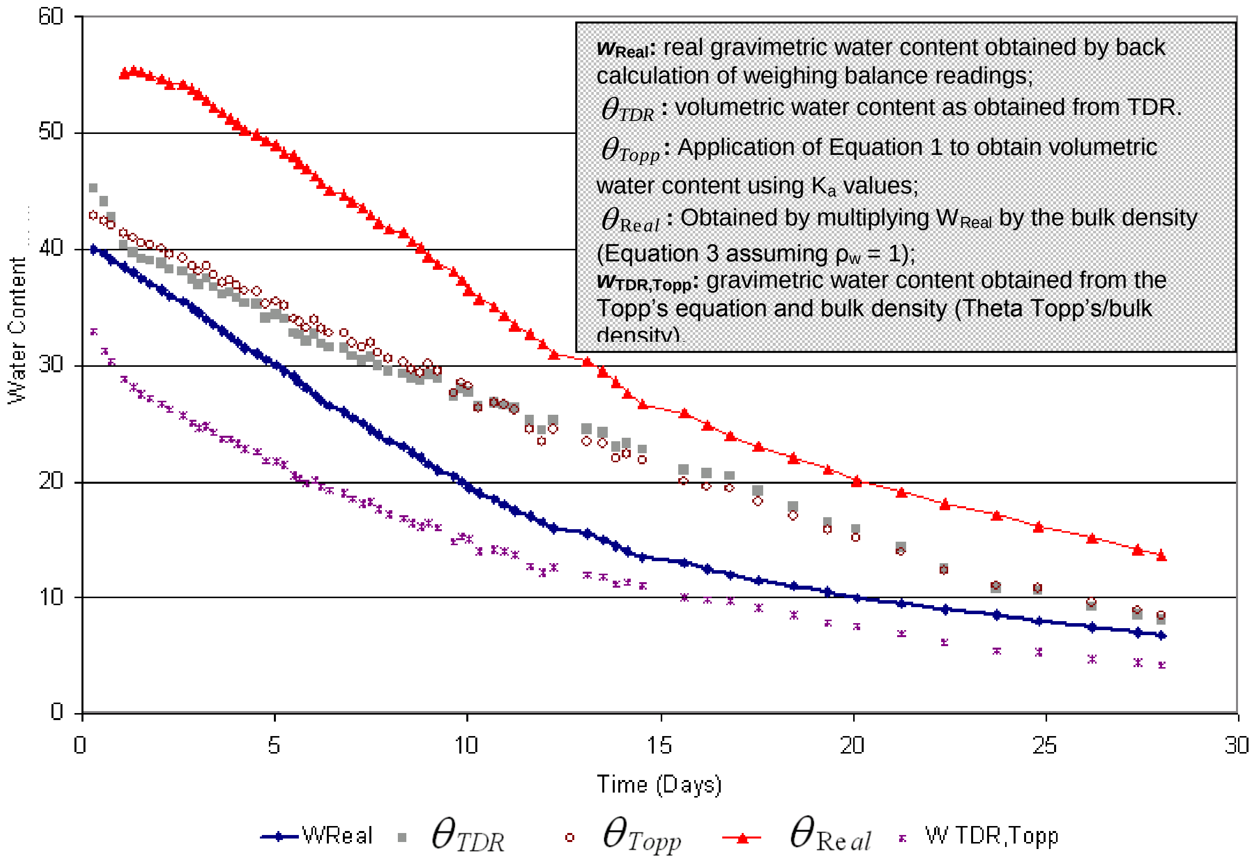

Figure 3. Comparison between the non-calibrated TDR readings and the real gravimetric (kg/kg) and volumetric (m^3/m^3) water content values as estimated by the shrinkage curve experiment.

The objective of this study is to improve the predictability of TDR equipment for the water content of swelling soils. Thus, the coefficients of the Topp's equation (Equation 1) were calibrated through optimization that minimizes the sum of the square of the error between the real and predicted volumetric water content (Equation 4.a). Similar empirical form of the Topp equation was obtained for the gravimetric water content as function of K_a by minimizes the sum of the square of the error between the real and predicted gravimetric water content (Equation 4.b). Figure 4 shows a comparison between the calibrated TDR readings and the real gravimetric and volumetric water content values showing an excellent fit between the real and the four-parameter Topp's equation (after calibration).

$$\theta_{TDR,calibrated} = 9.79\times10^{-2} + 5.01\times10^{-4} k_a + 1.84\times10^{-3} k_a^2 - 4.56\times10^{-5} k_a^3 \quad \text{Equation 4.a}$$

$$w_{TDR,calibrated} = 9.55\times10^{-2} - 1.18\times10^{-2} k_a + 1.7\times10^{-3} k_a^2 - 3.3\times10^{-5} k_a^3 \quad \text{Equation 4.b}$$

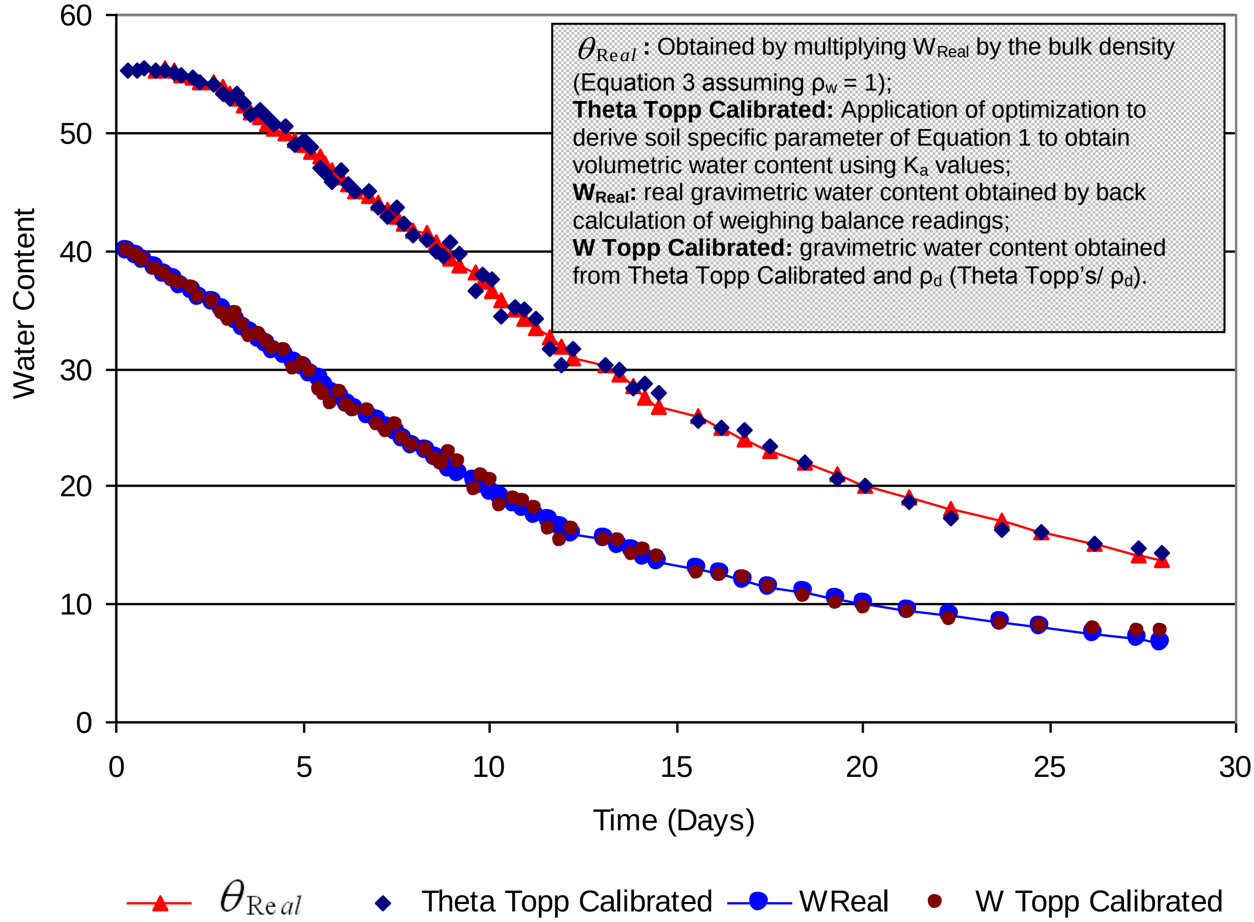

Figure 4. Comparison between the calibrated TDR readings and the real gravimetric (kg/kg) and volumetric (m^3/m^3) water content values as estimated by the shrinkage curve experiment.

Comparison with Siddiqui and Drnevich Equation

In addition to comparison with the Topp's Equation, the Siddiqui and Drnevich Equation was utilized in two ways: (1) using a single value of ρ_d obtained from the shrinkage curve and (2) using the real ρ_d as function of w.

First, the *a* and *b* parameters of Equation 2 were obtained by minimizing the square of the error $(w_{Real} - w_{TDR\_Single\ BD})^2$ using the Microsoft Excel optimization solver assuming constant value of bulk density. An interesting observation was that the optimized values of $w_{TDR\_Single\ BD}$ followed the same curve irrespective of the choice of ρ_d (or BD). However, the *a* and *b* parameters decreased as ρ_d increased (or w_{Real} decreased). Table 1 shows the results of the *a* and *b* parameters for three ρ_d values taken at w_{Real} = 40%, 20% and 6.75%. Figure 5 shows a considerable improvement in the predictability of the water content using Equation 2 (for *experiment 1*). However, error (w_{Real}- $w_{TDR\_Single\ BD}$)^2 was still within five water content percentage points over a considerable portion of the experimental range.

Table1. Variation in the a and b parameters for *experiment 1*.

	Assuming constant ρ_d at W_{Real} = 40%	***Assuming constant ρ_d at W_{Real} = 20%***	***Assuming constant ρ_d at W_{Real} = 6.75%***	***Assuming dynamic ρ_d as predicted by the ShC***
a	1.45	1.12	1.03	0.60
b	5.79	4.45	4.10	7.56

Further improvement of TDR prediction using the Siddiqui and Drnevich Equation was achieved by solving for *a* and *b* after substituting the corresponding value of ρ_d (function of *w*) to obtain gravimetric water content predictions using K_a, ρ_d, and calibrated *a* and *b* values (w_{TDR_ShC}). The *a* and *b* were also obtained by minimizing the square of the error (w_{Real}- w_{TDR_ShC})^2 (Table 1). Figure 5 shows an excellent match between w_{Real} and w_{TDR_ShC}. This shows the importance of the shrinkage properties of soils in predicting the water content using the two-parameter Siddiqui and Drnevich Equation 2. Statistically, the coefficient of determination, R^2, improved from 0.9664 to 0.9846 when changing from single bulk density value to a variable value that is a function of *w*. Similarly, the mean absolute error improved from 1.50 to 0.85 percentage points for gravimetric water contents when changing from single bulk density value to values as function of *w*.

To demonstrate the uniqueness of this approach for a given soil type, the analysis performed from the first experiment (*experiment 1*) was tested on *experiments 2* and *3* using the parameters from *experiment 1*. Here, uniqueness is defined as the repetitiveness of the obtained parameters from one experiment to the others if the same soil type is used. Results will be discussed in the next section.

Discussion

Results of the second and third experiments were analyzed similar to *experiment 1* (the three experiments utilized three replicates of the same soil). Results were first analyzed with the complete dataset for each experiment. The shrinkage process changes quickly at high water contents and becomes very slow at low water contents (Figure 2). This means that all the datasets in the three experiments have more data points per unit of w_{Real} at low water contents and this may affect the results of the optimization process, whether calibrating for the soil-specific four parameters of the Topp Equation or for *a* and *b* for the Siddiqui and Drnevich Equation. Thus, to provide a uniform distribution of the dataset across the range of water contents, datasets were rearranged by considering only one representative data point for each half percentage point of w_{Real}.

The uniqueness of this method was tested by substituting the values of *a* and *b* obtained for *experiment 1* to *experiments 2* and *3*. Figure 6 shows a comparison between w_{Real} and w_{TDR_ShC}. An excellent match between w_{Real} and the predicted w_{TDR_ShC} is observed for the three experiments based on using the *a* and *b* values of *experiment 1*. However, it was observed that at w_{Real} values higher than 39%, the w_{TDR_ShC} consistently over-predicted w_{Real}. This means that above a certain threshold value of w_{Real}, Equation 2, or the procedure adopted in this analysis, fails to predict the gravimetric water content of the soil. Thus a physical meaning for the threshold w_{Real} value needs to be established or else the predictability of water content by Equation 2 may not be unique or reliable.

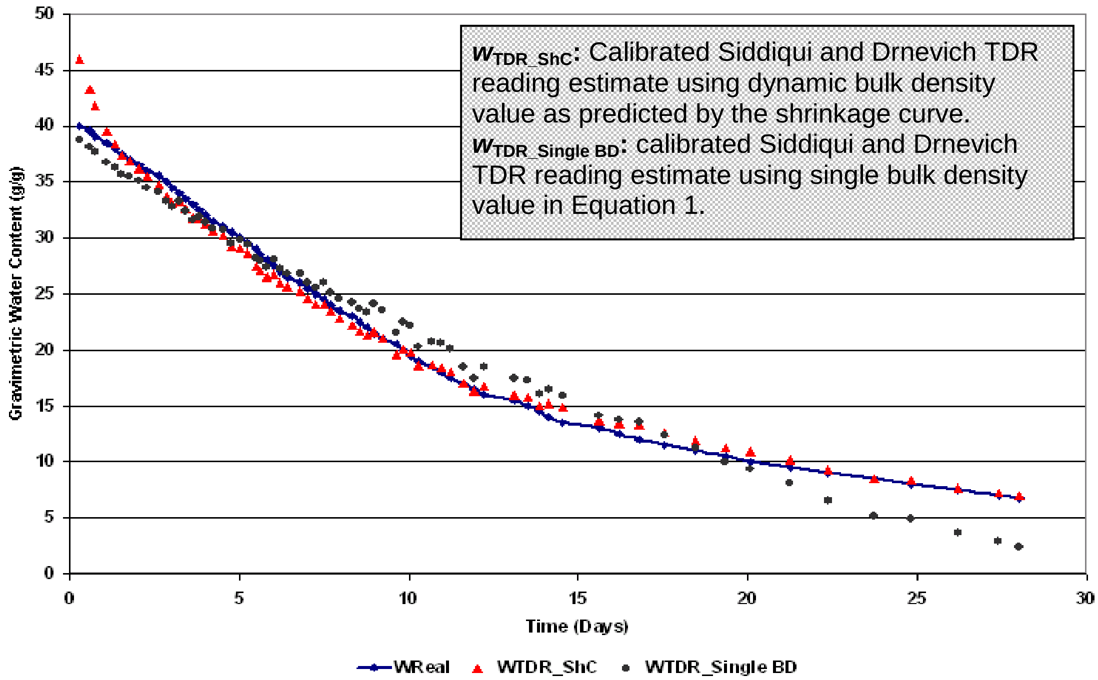

Figure 5. The performance of the Siddiqui and Drnevich Equation in estimating W demonstrated through a comparison between W_{Real} and $W_{TDR\_SingleBD}$ (as estimated by Equation 2 and a single bulk density value) and W_{TDR_ShC} (as estimated by Equation 2 and a dynamic bulk density value) for *experiment 1*.

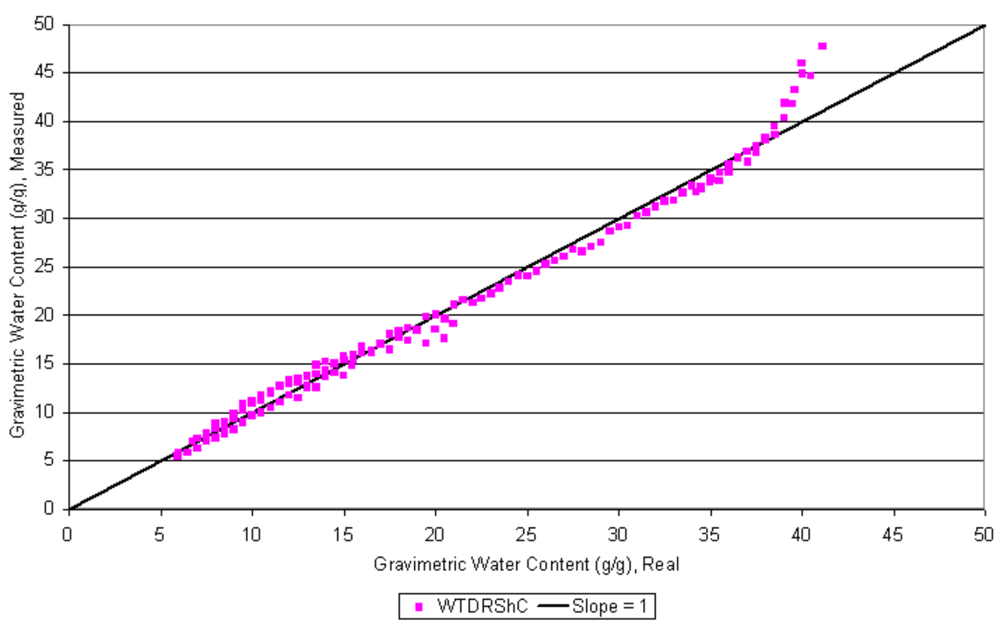

Figure 6. Results of the three experiments showing the effectiveness of accounting for the change in the soil bulk density in improving TDR predictions. The *a* and *b* of *experiment 1* were used for *experiment 2* and *experiment 3*.

The search for a physical explanation to the threshold value above which Equation 2 over predicts w_{Real} triggered the attention towards the shrinkage curve. By mapping the shrinkage curve over w_{Real} vs. w_{TDR_ShC}, it was observed (Figure 7) that the same threshold value above which w_{TDR_ShC} over predicts w_{Real} is the air entry point of the macro structure in the shrinkage curve (as explained by Braudeau *et al.*, 2004). This point is defined when the slope of the shrinkage curve becomes less than one thus implying that the soil is no more at saturation. Physically, it means that the change in volume of the soil is less than the change in w_{Real} with some of the pores filled with water becoming filled with air (instead of being totally lost to volume change). For TDR, this means that Equation 2 may best predict the gravimetric water content of the soil when the soil is at or below the saturation limit. At much higher water contents, the soil may act as a slurry more than a soil and it is assumed that this is the reason why TDR over predicted the water content in that range.

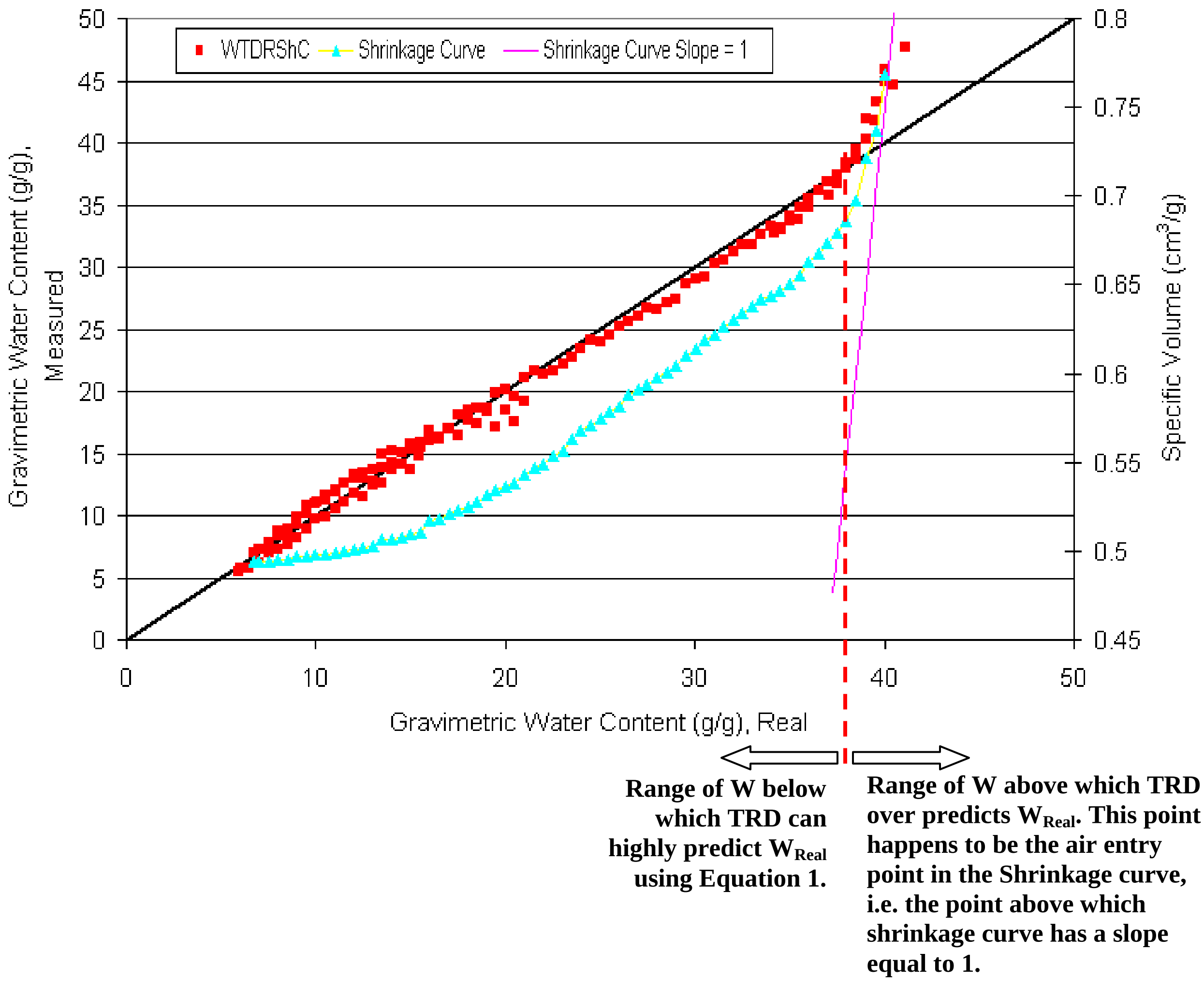

Figure 7. The use of the Shrinkage Curve to define threshold for TDR predictability.

Relevance to the Industry

Relevance to industry comes through incorporating the effect of the soil structural interactions by accounting for the soil dynamic shrinkage/swelling behavior in the calculation of the soil bulk density. This can be achieved by allowing users to enter the unique shrinkage/swelling curve parameters as part of the input in the TDR equipment. This however requires one further step that is to translate the x-axis of the shrinkage curve from w_{Real} to K_a. The reason is that TDR measures K_a directly and infers θ_{TDR} or w_{TDR} by relating K_a to the volumetric or gravimetric water content through Equations 1, 2, and/or 3. Thus, the TDR equipment would require all models to be a function of K_a rather than w or θ. Moreover, accounting for volume change improved the predictability of the gravimetric water content by the TDR equipment simply because Equation 2 contained the bulk density term (which makes it more physically based than Topp's Equation which is totally empirical). Accordingly, incorporating volume change properties of the soil in TDR equipment requires mapping the soil shrinkage/swelling properties into a unique relationship with K_a as demonstrated in Figure 8.

It is proposed that this research be extended to the swelling direction. This can be achieved by slightly modifying the experimental procedure by allowing for adding water to a dry soil specimen, and again taking TDR and electronic balance readings at fixed time intervals. In all cases, shrinkage/swelling behavior can be incorporated into the new TDR equipment by relating those properties to K_a for a given soil and include them in the calculations for the next generation of TDR equipment.

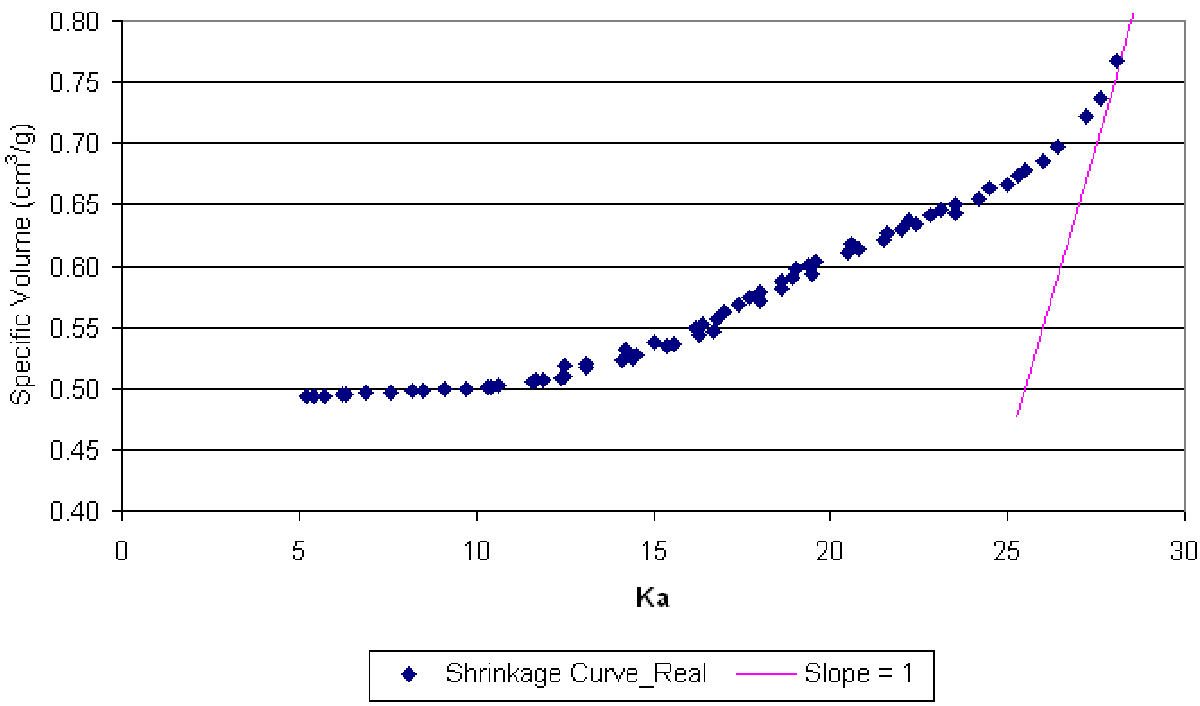

Figure 8. Shrinkage Curve as function of K_a instead of W_{Real}.

Predicting the Shrinkage Curve

Gravimetric and volumetric water contents interact in a unique relationship (Equation 3) that can be re-written as:

$$\frac{w}{\theta \rho_w} = \frac{1}{\rho_d} = SpecificVolume \qquad \text{Equation 5}$$

Thus, if *w* and θ can be predicted by the TDR, then the specific volume of the soil can be calculated using Equation 5.

To test this hypothesis, five points from *experiment 3* were considered (Table 2). The values for *w* and θ vs. K_a were used to construct a cubic polynomial constitutive relationship similar in form to the Topp's Equation (Figure 9). This allows for the prediction of *w* and θ for every value of K_a as explained in Equations 6 and 7:

$$\theta_{TDR,Calibrated} = 9.6\times10^{-2} - 4.3\times10^{-3}k_a + 2.7\times10^{-3}k_a^2 + 7.0\times10^{-5}k_a^3 \qquad \text{Equation 6}$$

$$W_{TDR,Calibrated} = 4.15\times10^{-2} + 2.00\times10^{-4}k_a + 1.1\times10^{-3}k_a^2 - 2.0\times10^{-5}k_a^3 \qquad \text{Equation 7}$$

Using Equation 5, estimates of the specific volume of the soil in *experiment 1* were plotted against the gravimetric water content (i.e. the shrinkage curve) and compared to the real shrinkage curve of *experiment 1* (Figure 10). Although results are not a perfect match, the fact that such an estimate of shrinkage curve of *experiment 1* was obtained from calibration of five data points of a different soil replicate (*experiment 3*) make this method a promising tool to estimate the bulk density of the soil, and definitely an application worth considering for TDR equipment.

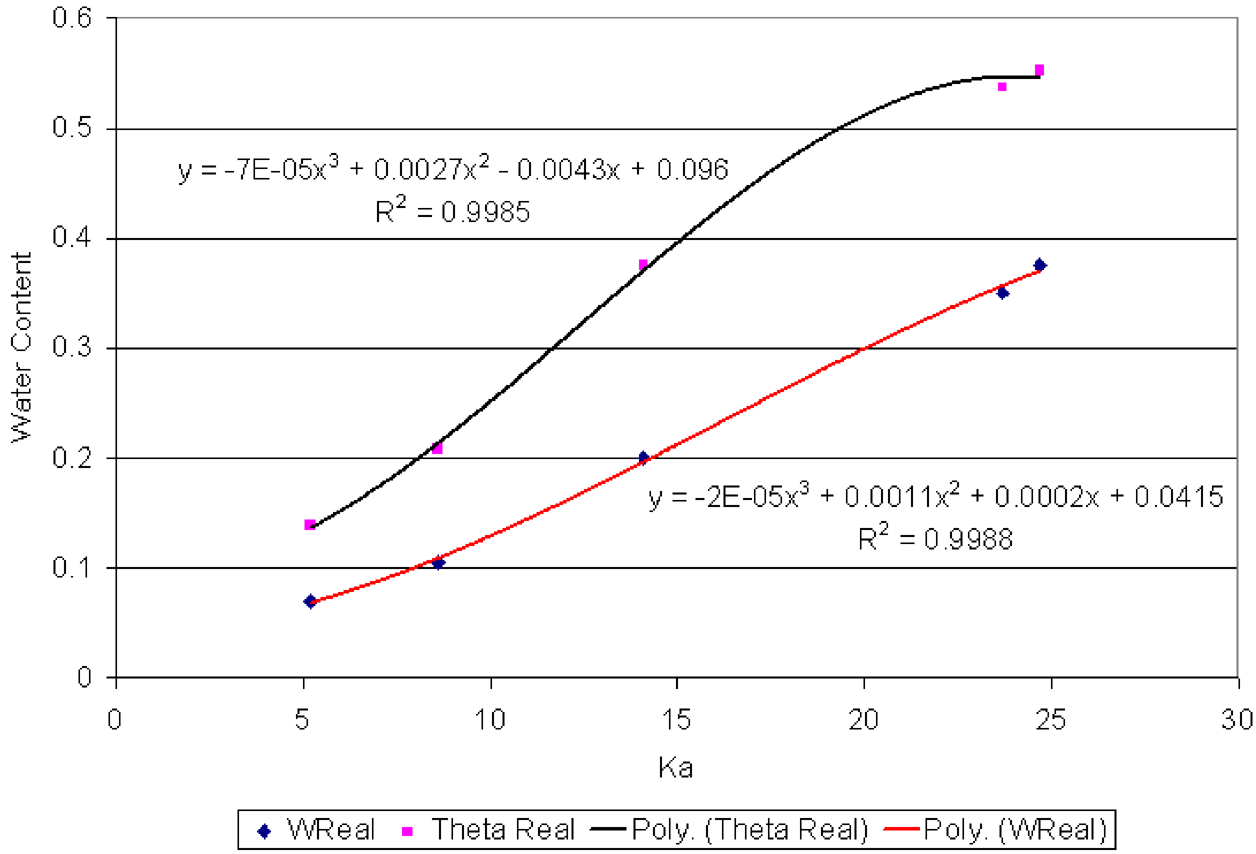

Figure 9. Calibration of the gravimetric and volumetric water content predictions using Topp's-like polynomial equations estimated from five experimental points in *experiment 3*.

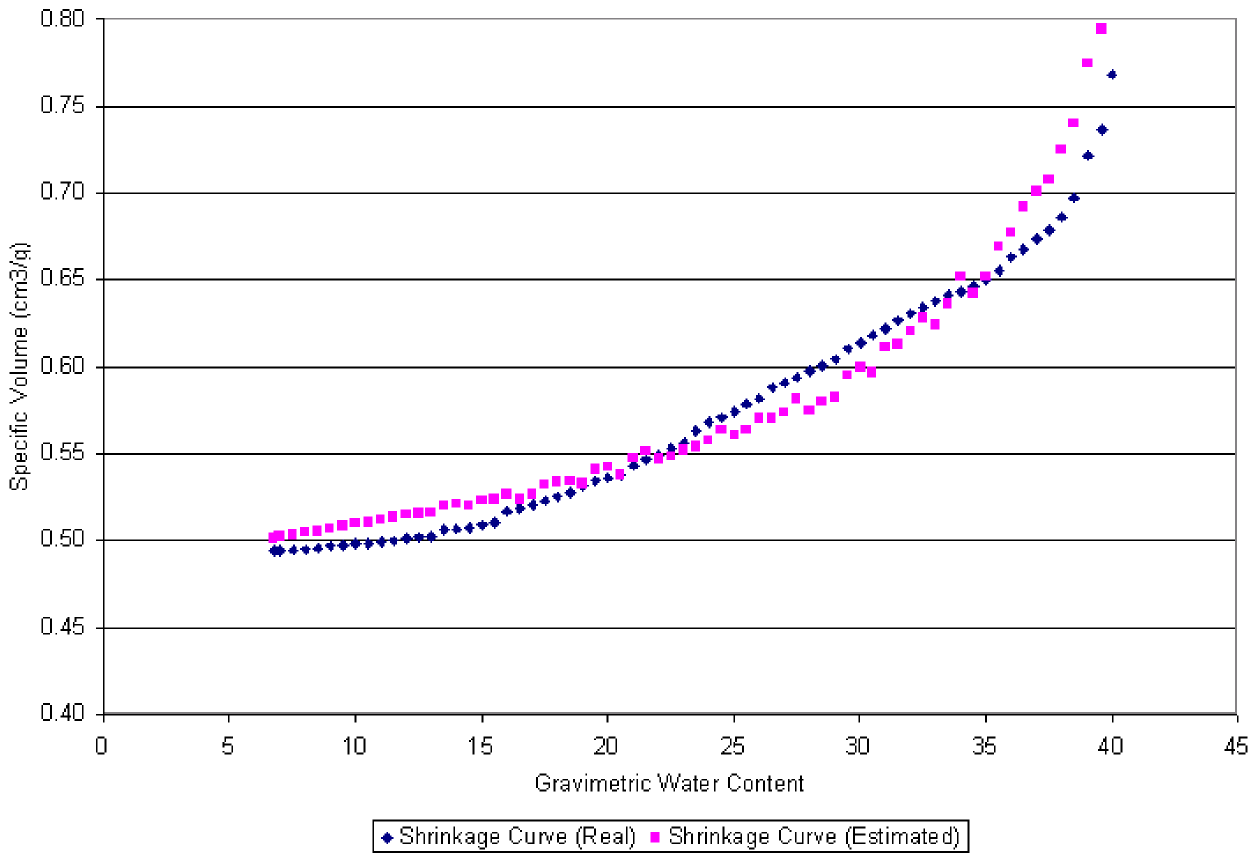

Figure 10. Comparison between the real shrinkage curve of *experiment 1* and the predicted curve based on calibrated gravimetric and volumetric water content predictions using Topp's-like polynomial equations estimated from only five experimental points in *experiment 3*.

Table2. Five data points from *experiment 3* used to estimate the shrinkage curve of *experiment 1*.

Point	*Ka*	*WReal*	θ_{Real}
1	24.7	37.5	55.3
2	23.7	35.0	53.7
3	14.1	20.0	37.6
4	8.6	10.5	20.8
5	5.2	7.0	13.9

Conclusion

TDR equipment provides accurate predictions of the soil volumetric and gravimetric water content through direct measurement of the apparent dielectric constant of the soil, K_a. Experimental evidence was provided to demonstrate the effect of soil shrinkage on improving the accuracy of water contents from TDR measurements. Direct water content calculation for the Chalmers soil was compared to TDR readings *with* and *without* shrinkage correction and showed considerable improvements in soil moisture by accounting for soil shrinkage. This work provides experimental evidence on the importance of incorporating the volume change behavior of soils into TDR equipment for improving the predictability of volumentric water content (θ) or gravimetric water content (w) as follows:

1. Comparison between direct measurements of θ or w and indirect measurements using TDR's factory built-in parameters showed unsatisfactory accuracy for swelling soils.
2. Improving the predictability by solving for soil-specific parameters assuming a single bulk density value (thus no volume change) showed considerable improvement, but errors up to five water content percentage points at high and low extremes in water contents occurred with the Siddiqui and Drnevich Equation.
3. Accounting for volume change by substituting the corresponding value of ρ_b in the Siddiqui and Drnevich Equation for each w estimation demonstrated very accurate predictability of gravimetric water content by the TDR equipment below a certain threshold.
4. This threshold was defined as the point of soil saturation in the shrinkage curve, above which the soil behaves as slurry.
5. By defining soil-specific parameters for the estimation of volumetric and gravimetric water contents, the bulk density (or specific volume) of the soil can be estimated with considerable accuracy (Equation 5).

Finally, it was proposed that the outcome of this research will form the first steps towards next generation of TDR data analysis algorithms that can account for volume change properties of the soil by allowing for user-input of the shrinkage/swelling properties and parameters of the soil.

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