# Indirect measurements of water content using TDR-inferred dielectric permittivity and electrical resistivity

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**Abstract.** The measurement of moisture distribution in Engineered Barrier Systems (EBS) in salt mines and deep geological disposals is essential in order to monitor fluid ingress and record data for long-term security analyses. Additionally, soil moisture content has influence over the mechanical properties of the soil as well as plant growth, soil stability and contaminant transport to cite some. Therefore, finding affordable and reliable ways to determine moisture content, quickly and in the field without sampling, is of great interested among people in different subject areas. Time-domain reflectometry (TDR) has become a recognized electromagnetic method for non-destructive measurement of dielectric permittivity and electrical conductivity of moist porous materials. It turns out that both these measurements depend on the material moisture content, among other things. This paper presents a series of calibration tests performed on soil samples. TDR probes were used to obtain the dielectric permittivity and electrical conductivity of the samples. As a consequence, relationships between these measurements and the samples' volumetric water content were later established. These relationships can then be used to indirectly determine that important information of water content on similar soil material using cheap, quick and non-destructive TDR probes.

## 1 Introduction

Soil moisture is a part of the three phase system of the soil, which includes soil minerals (solids), moisture and air [1]. Hence, soil moisture content has quite significant influence on engineering, agronomic, geological, ecological, biological and hydrological behaviour [2] of the soil mass. Mechanical properties of the soil, consistency, cracking, swelling, shrinkage and density are dependent on the soil moisture content [1–2]. Moreover, it has a major role to play on plant growth, organization of the natural ecosystems and biodiversity [3]. Soil moisture content is also used as an important parameter for water balance studies, slope stability analysis and performance evaluation of various geotechnical structures such as pavements, foundations, earth dams, retaining walls, hazardous waste disposal repositories and contaminant transport within the vadose zone [4]. In sum, physical, chemical, mineralogical, mechanical, geotechnical, hydrological and biological properties of the soils are significantly dependent on soil moisture content [3].

There are various methods for assessing soil moisture content, including the gravimetric method, which is one of the most widespread and easiest, and methods that use soil physical properties related to moisture to indirectly estimate the soil water content, including temperature, electrical resistance, capacitance, spectrometry and time-domain reflectometry (TDR) [3], amongst others.

In this paper, TDR probes were used to obtain the apparent permittivity and electrical conductivity of four different soil samples. Relationships between these measurements and the samples' volumetric water content were later established.

## 2 Background

In TDR measurement in soil an electromagnetic pulse is transmitted into the soil where parallel transmission lines serve as a "wave" guide. The velocity of the pulse travelling in the soil which is determined by TDR is a measure of the permittivity of the soil.

A TDR system consists of a step pulse generator, an oscilloscope, a coaxial cable and a rod probe. The step pulse generator launches a fast rise time voltage step associated with a bandwidth up to 1.5 GHz and the reflection waveform is recorded by an equivalent time sampling oscilloscope [5].

The apparent permittivity, $K_a$, of the medium in which the TDR probe is inserted can be obtained from the propagation velocity of the pulse in the probe, in which:

$$K_a = \left(c\frac{\Delta t}{2L}\right)^2 \quad (1)$$

where $c$ is the velocity of electromagnetic signals in free space (3 x $10^8$ m/s), $\Delta t$ is the travel time for the pulse to travel the length of the embedded wave-guide ($\Delta t = t_2 - t_1$), $t_2$ is the time the step pulse leave the head and enters

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the probe electrodes and $t_1$ is the time at which the wave enters the head of the probe and $L$ is the waveguide length.

Topp et al. [6] was one of the firsts to suggested that the apparent permittivity, could directly be related to volumetric water content, *VWC*, through a polynomial calibration curve:

$$VWC = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \times K_a - 5.5 \times 10^{-4} \times K_a^2 + 4.3 \times 10^{-6} \times K_a^3 \quad (2)$$

The authors [6] suggested that Equation (2) was almost independent of soil density, texture, temperature, and salt content. This equation was derived for volumetric water contents between 0.02 to 0.55 and dry densities between 1 to 1.5 g/cm$^3$.

Over the years, other researchers have shown that the relationship between *VWC* and $\sqrt{K_a}$ is practically linear and other empirical relationships have been stablished, amongst the most popular is the equation proposed by Ledieu et al. [7]:

$$VWC = 0.1138 \times \sqrt{K_a} - 0.1758 \quad (3)$$

However, later studies have shown the dependency of the VWC–$K_a$ relationship on clay content [8] and mineralogy [9] soluble salt content [8–10], and organic matter and porosity or soil density [8–11].

Thus, Malicki et al. [11] have proposed a different empirical formula to include the effect of soil density, that has been shown to affect $K_a$:

$$VWC = \frac{\sqrt{K_a} - 0.819 - 0.168\rho_d - 0.159\rho_d^2}{7.17 + 1.18\rho_d} \quad (4)$$

where $\rho_d$ is the dry bulk density (g/cm$^3$).

To determine the sample's electrical resistivity, $\rho$, using TDR waveforms, Giese & Tiemann [12] have proposed the following equation:

$$\rho = \alpha \frac{1+\rho_{corr}}{1-\rho_{corr}} \quad (5)$$

where $\alpha$ is a calibration constant and $\rho_{corr}$ is a correction proposed by Castiglione & Shouse [13] to the reflection coefficient at infinite time, $\rho_\infty$, obtained through the TDR in witch:

$$\rho_{cor} = 2\frac{\rho_\infty - \rho_{air}}{\rho_{air} - \rho_{sc}} + 1 \quad (6)$$

where $\rho_{air}$ is the reflection coefficient obtained when the probe is in open circuit (air) and $\rho_{sc}$ is the reflection coefficient when the probe is in short circuit.

## 3 Materials and methods

Four soils were used in this study: Speswhite Kaolin Clay (KAO) [14], Bentonite Clay (BEN) [15] and two naturally occurring soils: a Silty Sand material (ITA) from Ficulle, Italy, and a tropical silty soil (BSB), from Brasilia, Brazil [14]. The particle size distribution of the material is presented in Fig. 1.

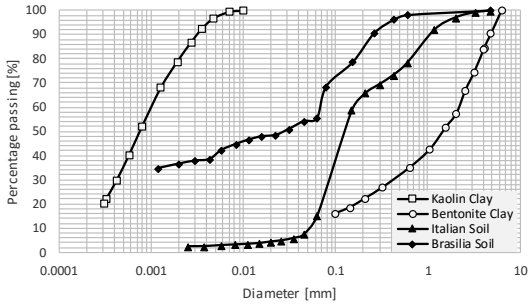



**Fig. 1.** Particle size distribution of all four materials

Samples of KAO, ITA and BSB were prepared by manually mixing the air-dried material with distilled water (7.1 x 10$^{-4}$ dS/m). Samples of BEN were prepared by manually mixing the air-dried material with synthetic water (4 dS/m) representative of the Callovo-Oxfordian argillite at Bure, France. BEN samples were prepared with this synthetic water because the results related to these samples and presented here were used comparatively with a series of other tests within 'Modern 2020' project. Those test are beyond the scope of this paper and are therefore not presented here. All samples were prepared and left to equilibrate in a sealed bag for 24 hours.

All samples were then placed in an acrylic mould, internal dimensions of 8.82cm in diameter and 3.10cm in height. A TDR probe (CS640, Campbell Scientific 7.5cm long rods, $L$ = 0.075m) was then inserted into the sample.

Two waveforms were acquired with the help of the TDR probe, one with a short window interval of 10ns, for determination of $K_a$ and a second one with a long window interval of 200ns for determination of reflection coefficient at infinite time, $\rho_\infty$.

Calibration measurements were required to determine both parameters. 10ns waveforms were recorded when the probe was left in air and immersed in demineralised water to obtain $t_1$. Time $t_2$ was obtained for each sample using an algorithm developed and implemented in LabVIEW at the Geomechanics laboratory of University of Strathclyde following the procedures described by Tarantino et al. [5]. Then $K_a$ was obtained using equation (1). Equations (2), (3) and (4) were used to empirically derive the *VWC* of the samples that were later compared with their measured *VWC*.

200ns waveforms were recorded when the probe was left in air and short circuited in a metal plate to obtain $\rho_{air}$ (0.978) and $\rho_{sc}$ (-0.933) respectively. The calibration constant, $\alpha$, for the TDR probe used in this research was obtained through a calibration process, in which the TDR probe was immersed in different NaCl concentration solutions of known conductivity and their 200ns waveforms were recorded. The slope of the resulting relationship between the reflection coefficients at infinite time and their theoretical conductivities is $\alpha$ equal to 8.482Ωm.

The reflection coefficient at infinite time was obtained through the waveform of the 200ns window interval by averaging the last 50 points of the reflection curve. The

resistivity of the samples was calculated using equations (5) and (6).

After that, a small specimen was collected with a sampler of known volume (3.68cm$^3$) for the determination of the volumetric and gravimetric water content.

Finally, for the BEN samples only, another specimen was collect for the determination of the total suction in the dewpoint psychrometer. The psychrometer used in this experimental programme is a product of Decagon Devices, Inc. (Pullman, WA, USA) and is known as a WP4 Dew Point Potentiameter.

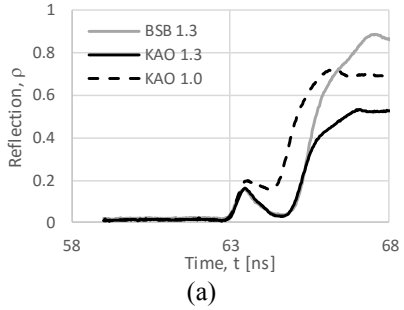
## 4 Results and discussions

Fig. 2 shows the short and long window waveforms of three samples. Firstly, let us compare both KAO samples. As presented in Table 1, those two samples have similar *VWC* ($S_d$ = 0.02) and are made of the same material. The difference between these samples are the density. Results show two distinct reflection curves that leads to distinct $K_a$ and resistivity values, which suggests that both parameter are dependent on density. Although the difference in resistivity between the two KAO samples can be down to the slight difference in *VWC*.

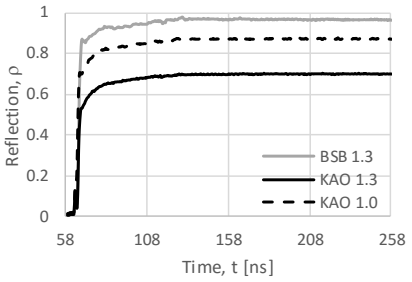
Now, comparing BSB and KAO samples, which have similar *VWC* and density, one can see that at the beginning of the reflection, on the short window waveform, the curves are almost identical until the first reflection, which produces similar $K_a$ values, however the reflection coefficient at infinite time is very different between these two samples, which leads to distinct resistivity measurements. These comparisons suggest that density is more relevant to $K_a$ than the nature of the material, at least between these two soils. Resistivity on another hand seems to be affected by both density and type of soil.

**Table 1.** BSB and KAO sample characteristics

| Material | BSB | KAO | KAO |
|---|---|---|---|
| Label on graph | BSB1.3 | KAO1.0 | KAO1.3 |
| Density (g/cm$^3$) | 1.3 | 1.0 | 1.3 |
| *VWC* | 0.27 | 0.26 | 0.29 |
| *VWC* (Topp) | 0.27 | 0.16 | 0.26 |
| *VWC* (Ledieu) | 0.29 | 0.15 | 0.25 |
| *VWC* (Malicki) | 0.35 | 0.23 | 0.32 |
| $K_a$ | 16.408 | 8.407 | 14.239 |
| $\rho$ (Ωm) | 1465 | 147 | 49 |




(a)




(b)

**Fig. 2.** Waveform for samples of KAO and BSB (a) 10ns window and (b) 200ns window

Bearing in mind the conclusions drawn from the results presented in Fig. 2, samples prepared from this point forward were also controlled in terms of density. Thus the average density of all BEN, BSB, KAO and ITA samples was 1.43, 1.16, 1.01 and 1.47g/cm$^3$ respectively while the standard deviation was 0.03, 0.06, 0.19 and 0.15g/cm$^3$ respectively.

Fig. 3, Fig. 5, Fig. 7 and Fig. 9 show the dispersion between measured and estimated *VWC* using equations (2), (3) and (4) for BEN, BSB, KAO and ITA samples respectively, while Fig. 4, Fig. 6, Fig. 8 and Fig. 10 show the measurements of apparent permittivity plotted against measured and estimated *VWC* for BEN, BSB, KAO and ITA samples respectively.

Table 2 shows the fitting equations and their respective $R^2$ values for the empirical relationships established between measured *VWC* and $K_a$ for BEN, BSB, KAO and ITA samples.

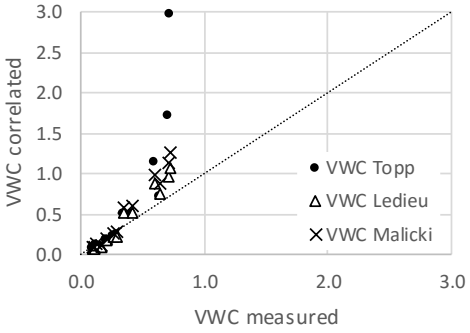



**Fig. 3.** *VWC* measured and correlated, BEN samples

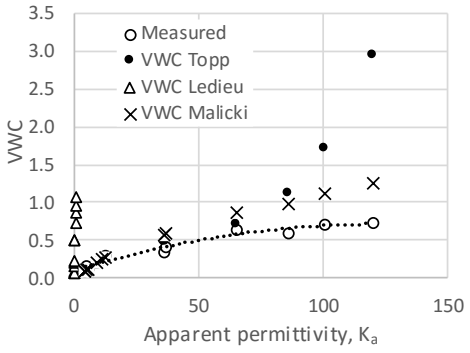



**Fig. 4.** *VWC* versus $K_a$, BEN samples

The dispersion plot of BEN samples presented in Fig. 3 shows that for *VWC* between 0 and 0.4, empirical equations (2) and (3) underestimate slightly the *VWC*, while equation (4) gives an almost precise *VWC* result. However, for values higher than 0.4 the *VWC* produced by all empirical equations deviates significantly from the measured *VWC*, to an extreme point of producing impossible values (higher than 1), with equation (2) producing the worst fitting. A similar observation can be obtained based on the relationship shown in Fig. 4, and in fact Tarantino et al. [5] suggested that Topp's equation (2) should not be used for *VWC* beyond 0.45.

Similarly, to BEN samples with *VWC* lower than 0.4, the other three materials have showed similar trends, where the three empirical equations tested either slightly underestimate or overestimate the *VWC*, with equation (4) performing better than the other equations. The good agreement achieved between empirical equations and measured *VWC* in the cases of BSB and ITA samples is clearly related to the range of *VWC* within the samples tested, which are lower than 0.4. Surprisingly, the empirical equations also performed well on KAO samples with *VWC* higher than 0.4.

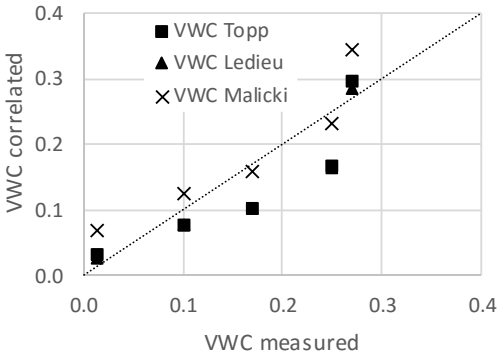



**Fig. 5.** *VWC* measured and correlated, BSB samples

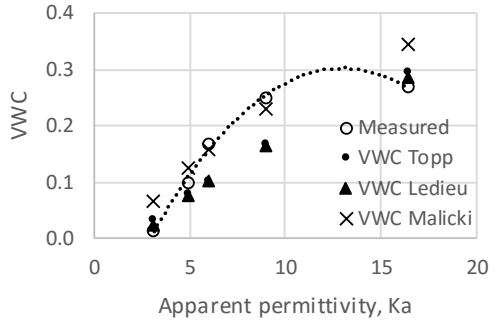



**Fig. 6.** *VWC* versus $K_a$, BSB samples

**Table 2.** Empirical relationship between measured *VWC* and $K_a$

| Soil | Fitting equation | $R^2$ |
|---|---|---|
| BEN | $y = -4E\text{-}05x^2 + 0.0099x + 0.1017$ | 0.9642 |
| BSB | $y = -0.0029x^2 + 0.0767x - 0.197$ | 0.9946 |
| KAO | $y = -0.0005x^2 + 0.0317x - 0.0252$ | 0.9768 |
| ITA | $y = -0.0005x^2 + 0.031x - 0.0828$ | 0.9900 |

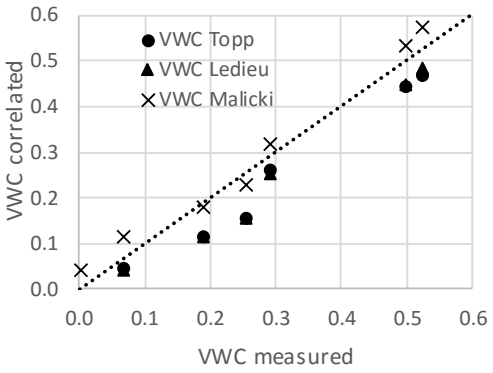



**Fig. 7.** *VWC* measured and correlated, KAO samples

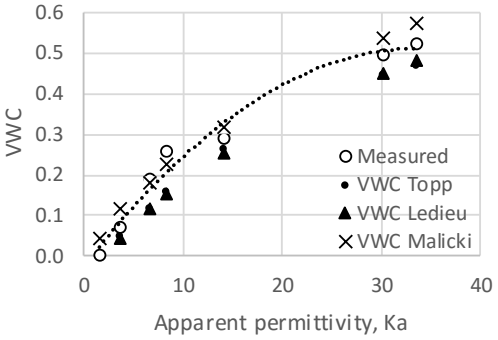



**Fig. 8.** *VWC* versus $K_a$, KAO samples

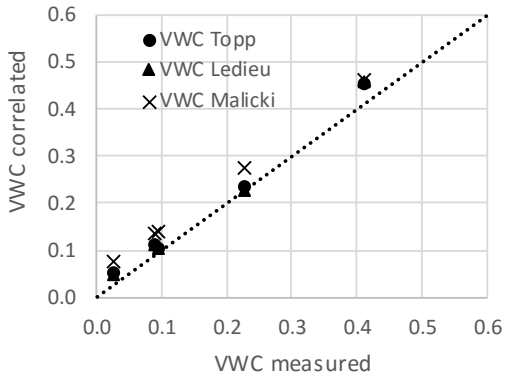



**Fig. 9.** *VWC* measured and correlated, ITA samples

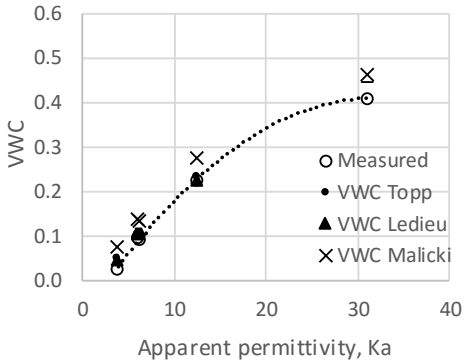



**Fig. 10.** *VWC* versus $K_a$, ITA samples

Fig. 11 presents the resistivity values calculated according to equations (5) and (6) of all samples plotted against the measured *VWC*, while Table 3 shows the fitting equations and their respective $R^2$ values for the empirical relationships established between measured *VWC* and resistivity of all samples.

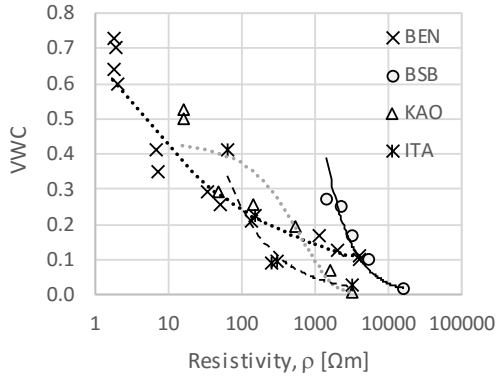



**Fig. 11.** Electrical resistivity versus *VWC*

The relationship between *VWC* and resistivity amongst BEN, KAO and ITA samples follow a power law, which is commonly seen in the literature [16–18]. The trend followed by KAO samples however is an exponential law (Table 3).

**Table 3.** Empirical relationship between Resistivity and measured *VWC*

| Soil | Fitting equation | $R^2$ |
|---|---|---|
| BEN | $y = 0.6982x^{-0.229}$ | 0.9710 |
| BSB | $y = 4809.5x^{-1.291}$ | 0.9399 |
| KAO | $y = 0.4341e^{-0.001x}$ | 0.9685 |
| ITA | $y = 6.584x^{-0.711}$ | 0.9440 |

Not only soil moisture content is a key information, but the pore water phase also contains important characteristics that are of interested from a hydro-mechanical, chemical and agricultural point of view, such as soil suction and salinity.

Soil suction is an important measure of soil water status, availability and mobility. Estimation of soil suction values is necessary in determination of soil water transport, soil water uptake, solute transport and other processes that affect soil in natural and man-made states [19]. For agricultural purposes for instance, monitoring of soil suction allows management of plant growth by proper irrigation [20–21], while in regards of hydro-mechanics, suction is generally recognised as one of the key factors governing the behaviour of unsaturated soils [22].

To assess the possibility of also indirectly determining suction using indirectly determined measurements of *VWC* Fig. 12 was produced. It shows the Soil Water Retention Curve (SWRC) of BEN material in terms of its *VWC* and total suction obtained independently from experiments performed during this research campaign. Samples for determination of the SWRC were prepared following the same procedures described here. The fitting series shown in the graph was obtained through the correlation proposed by van Genuchten [23]. In the plot two additional series can be observed. The series named *VWC this research* refers to pairs of points of *VWC* estimated using equation presented in Table 2 and measured suction (WP4) obtained in this research campaign, while series *VWC Ledieu* refers to pairs of points of estimated *VWC* (Equation (3)) and measured suction (WP4) also obtained within this research campaign. The choice of Ledieu's equation over the other two empirical equations presented here were based on the dispersion plot presented in Fig. 3. Results are considered acceptable for both *VWC* empirical equations used, with the empirical equation proposed in this research specifically for the BEN material performing unsurprisingly better.

The discrepancy between measured and estimated suction can be observed in Fig. 13. The procedure overestimates the values of suction when suction is larger than 6000kPa and underestimates values of suction when it is lower than 6000kPa for the BEN samples tested.

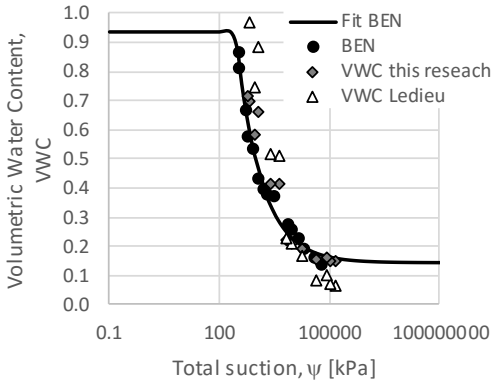



**Fig. 12.** Soil Water Retention curve for BEN samples

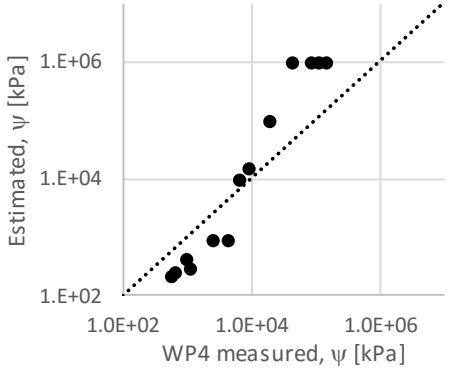



**Fig. 13.** Total suction measured and correlated, BEN samples

## 5 Final remarks

*VWC* was successfully estimated by all 3 empirical equations, through $K_a$ measurements of all four soil samples when the *VWC* of such samples was below 0.4. The advantage of Equation (2) and (3) over equation (4) is that the first two equations require only the knowledge of the apparent permittivity, which makes the estimation of *VWC* in the field very convenient.

For BEN samples with *VWC* higher than 0.4 the estimated *VWC* produced by all 3 empirical equations were lacking accuracy. For such cases, it is recommended a calibration study in order to derive a unique empirical equation relating the soil's apparent permittivity with its *VWC*.

Another possibility is to estimate the soil *VWC* through knowledge of its bulk electrical resistivity; however, it would require a laboratory calibration to

derive an empirical relationship for each soil in question. Previous studies were also able to determine the electrical conductivity of the pore water based on bulk electrical conductivity values of soil samples measured using TDR probes [24], however this investigation was out of the scope of this research.

Total suction measurements were successfully estimated from values of *VWC* determined from both Equation (3) and the empirical equation proposed in this research for BEN samples and the use of a pre-determined SWRC that served as a calibration curve.

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