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Experimental study on water content and density effects on dielectric permittivity of selected Victorian soils

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ABSTRACT: The use of electromagnetic (EM) techniques in site investigations is becoming increasingly common all over the world. Thus, it is imperative to thoroughly understand the effects of soil geotechnical parameters on soil electromagnetic properties. While focused on compaction, this study investigates the effect of dry density, water content and soil type on the dielectric properties of 3 soils from Melbourne (Victoria) at 1 GHz, using Frequency Domain Reflectometry (FDR). Understanding the relationships between soil dielectric properties with geotechnical parameters is a key step in developing correlations. Whilst the real dielectric constant is strongly linked to the volumetric water content, an inversely proportional trend has been found between dry density and the real dielectric constant, presumably affected by the soil specific surface area. Furthermore, based on the experimental data presented herein, the Dobson Soil Mixing Dielectric Model (SMDM) for estimating the real dielectric constant has been modified and improved.

1 INTRODUCTION

1.1 *Dielectric properties of soil*

Electromagnetic wave based measurement techniques rely on changes on dielectric constant or relative permittivity. Dielectric constant κ is a complex number that describes the behaviour of a material when it is subjected to an electrical field and can be represented as described in (Rinaldi & Francisca, 2006):

$$\kappa = \kappa^{'} - j\kappa^{''} \tag{1}$$

where κ′ and κ″ are the real and imaginary component of the dielectric permittivity and $j = \sqrt{-1}$. The real component κ′ represents the polarisability of the material and it is proportional to the number of dipoles that exist within the material. The out of phase (imaginary) component of permittivity κ'', is in phase with the conductivity σ. Therefore, losses due to polarisation and conduction are measured together by the imaginary dielectric constant. Thus, considering these losses, an effective imaginary dielectric constant can be expressed as (Santamarina, Klein, & Fam, 2001):

$$\kappa''_{eff} = \kappa'' + \sigma/(\omega\varepsilon_o) \tag{2}$$

where $\varepsilon_o \approx 8.85 \times 10\text{-}12$ F/m; ω is the angular frequency; and σ is the electrical conductivity of the sample at very low frequency. At high frequencies:

$$\sigma''_{eff} = \kappa''\omega\varepsilon_0 \tag{3}$$

where σ''_{eff} is the effective electrical conductivity..

1.2 *Dielectric mixing models*

Each phase of unsaturated soils has distinct real dielectric constants: κ′ = 1 for air, κ′ = (2 − 7) for soil solid particles, and κ′ ≅ 80 for water. Therefore, the average dielectric constant of soils is related to the dielectric constant of the individual phases, their volume fractions, their spatial distributions and their orientations relative to the direction of the incident electrical field. These can be captured by means of mixture models with the simplest model known as the Lichtenecker and Rother Model (LRM):

$$\kappa_{eff}{}^{\alpha} = \sum_i \frac{V_i}{V} \kappa_i{}^{\alpha} \tag{4}$$

where κ_i is the permittivity of phase *i*; V_i is the volume of phase *i*, V is the total volume of the soil; and α is a constant varying from -1 to 1 depending on the geometrical arrangement of the components (Lichtenecker & Rother, 1931). Based on the LR model, Dobson et al. (1985) proposed a semi-empirical model on the basis of measurements covering 5 soil types ranging from a sandy loam to silty clay. This model, known as SMDM, can be used for predicting the real dielectric constant of soils, for frequencies between 1.4 GHz to 18 GHz:

$$\kappa'_{soil} = \left[1 + \frac{\rho_b}{G_s}\left(\kappa'_s - 1\right) + \theta^{\beta'}{\kappa'_{fw}}^{\alpha} - \theta\right]^{\frac{1}{\alpha}} \quad (5)$$

which was further adjusted for Low Frequencies (300 MHz to 1.4 GHz) by Peplinski et al. (1995):

$$\kappa'_{soil_{(LF)}} = 1.15 \times \kappa'_{soil} - 0.68 \quad (6)$$

where ρ_b is the dry bulk density g/cm^3; G_s is specific gravity g/cm^3; κ_s' is the real dielectric constant of solid particles; θ is the volumetric water content; κ_{fw}' is the frequency dependent real dielectric constant of free water; $\alpha = 0.65$; and β' = a soil type dependent coefficient defined as:

$$\beta' = 1.2748 - 0.00519\, Sand\% - 0.00152\, Clay\% \quad (7)$$

It can be seen that the dielectric behaviour of the soil matrix is strongly linked to the volumetric water content θ, as confirmed by various experimental studies that suggested empirical correlations between soil dielectric constant and volumetric water content (e.g., Roth, Malicki, & Plagge, 1992; Topp, Davis, & Annan, 1980; Wensink, 1993). These correlations, however, appear to respond more accurately to the conditions that they were originally based upon (e.g., soil type and frequency).

The most widely used empirical correlation is known as the Topp correlation. Topp et al. (1980) has suggested that the apparent dielectric constant κ_a for low loss and nearly homogeneous materials is proportional to the real dielectric constant as:

$$\kappa_a = -76.7\,\theta^3 + 146\,\theta^2 + 9.3\,\theta + 3.03 \quad (8)$$

Very few studies have investigated the impact of density on the dielectric properties of soils. Some studies have reported a proportional trend between the real dielectric constant and dry density for dry samples (Dirksen & Dasberg, 1993; Lauer, Albrecht, Salat, & Felix-Henningsen, 2010; Salat & Junge, 2010).

This paper investigates the effect of compaction on the dielectric properties of different soil types (at 1 GHz) and aims to enhance and develop a better understanding of the effects of dry density (or compaction) on electromagnetic properties of soil.

2 METHODOLOGY

2.1 *Laboratory Testing*

2.1.1 *Soil sample characterisation*

Soil samples were collected from the greater Melbourne region, Australia, encompassing different Melbourne geological formations, which are categorised as Silurian and Tertiary (Newer Volcanic and Brighton Group) formations.

Geotechnical properties of soil samples were determined during the experimental program. Grain size distributions including sieve analysis (Standards Australia, 2009) and hydrometer tests (Standards Australia, 2003a) were conducted to classify the soil in accordance with Unified Soil Classification System (USCS). In addition, standard compaction tests (Standards Australia, 2003b) were performed to obtain the optimum moisture content and the corresponding dry density for each sample. Specific Surface Area for soil samples was estimated based on the correlation suggested in (Ersahin, Gunal, Kutlu, Yetgin, & Coban, 2006):

$$SSA = 0.042 + 4.23\, Clay\% + 1.12\, Silt\% - 1.16\, Sand\% \quad (9)$$

2.1.2 *Soil sample preparation*

To obtain homogeneous samples at specific water contents, an adequate amount of distilled water was added to a batch of oven dried soil based on the amount of dry soil present and then mixed thoroughly. The batch was allowed to equilibrate for at least 24 hours in a sealed container. Distilled water was used to minimise the introduction of any foreign ions to the mixture. Next, different densities were achieved as follows: instead of applying 25 blows per layer (standard compaction test), each specimen was prepared with a different number of blows at a given gravimetric water content. After each specimen was prepared, dielectric measurements were performed (explained in next section) and a small portion was taken out for gravimetric water content measurement by oven drying and subsequently, converted to volumetric water content, which is called water content hereafter in this manuscript. This method was repeated for the subsequent gravimetric water contents up to the saturation point.

2.1.3 *Soil dielectric measurements*

Soil dielectric properties were measured using an Agilent dielectric Slim Form Probe connected to a FieldFox Vector Network Analyser. Before each dielectric measurement, a three step calibration was performed. Then, each specimen was placed on a lab jack and moved towards the probe to minimise any error from cable or probe movements until a penetration of at least 10 mm was maintained. Measurements were conducted and the coefficient of reflection S_{11} was measured and was converted to real dielectric constant at 1 GHz by means of proprietary software (the full discussion of this conversion is beyond the scope this study). Errors associated with the electromagnetic measurements were minimised by 3 repeated measurements in a triangular pattern for each specimen, such that the measurements were representative of the entire specimen. Predrilling was adapted to all specimens to compensate for the ones which the probe insertion may have been hard otherwise.

3 EXPERIMENTAL RESULTS, ANALYSIS AND DISCUSSION

3.1 *Soil geotechnical properties*

Grain size distribution analysis has revealed that samples are categorised as (locally known) Brighton Group Sand (A), extremely weathered Silurian Mudstone (B) and Basaltic clay (C). Table 1 provides a summary of fine and coarse fractions as well as other parameters including, optimum gravimetric water content w_{opt}, the corresponding dry density $\rho_{dry\ (opt)}$ and the estimated Specific Surface Area A_s.

Table 1. Soil sample characteristics

Sample	**Clay**	**Silt**	**Sand**	$\mathbf{W_{opt}}$	$\mathbf{\rho_{dry\ (opt)}}$	$\mathbf{A_s}$
	(%)	(%)	(%)	(%)	(g/cm^3)	(m^2/g)
A (SP)	0	3	97	9	2.0	–
B (ML)	20	51	29	13	1.8	108
C (CH)	63	29	8	27	1.4	290

3.2 *Soil dielectric properties*

Having prepared the specimens and conducted the dielectric measurements for each soil, dielectric data was grouped based on volumetric water content and dry density. The effect of water content and dry density among other parameters, on soil dielectric properties, could therefore be explicitly investigated. Results of real dielectric constant measurements at 1 GHz frequency were compared against volumetric water content and density. In addition, results of measurements were compared against the SMDM model, whilst the Topp correlation was also examined in predicting the real dielectric constant.

3.2.1 *Real dielectric constant versus water content*

By increasing the volumetric water content, the number of dipoles in a soil matrix increases and this results in more polarisation under an electromagnetic field, hence a larger real dielectric constant (Santamarina et al., 2001). This behaviour is well illustrated in Figure 1 for all 3 samples. However, the rate of these proportional trends is different for each type of soil. This can be explained as follows. As the clay content in the soils increases, the number of water molecules bounded to the soil particle increases for a given water content due to the increase in the soil Specific Surface Area and this will result in a lower real dielectric constant at a given water content. The bound water molecules are tightly held by clay particles and are unable to move freely compared to free water molecules when subjected to an electromagnetic field hence, they exhibit a lower real dielectric constant.

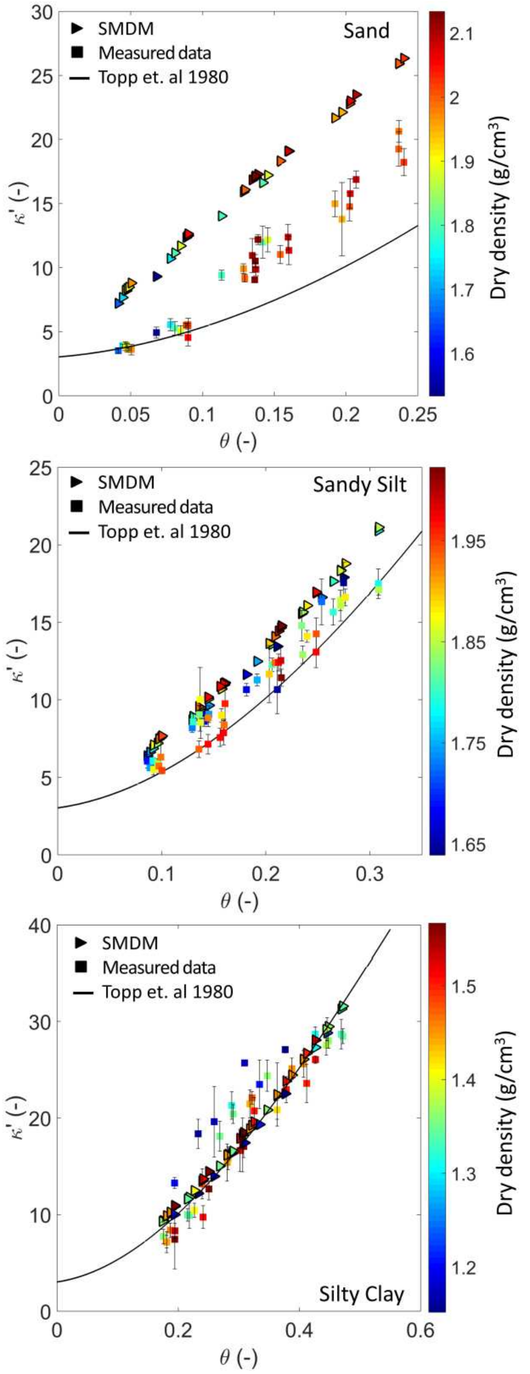

Figure 1. Real dielectric constant at 1 GHz compared against SMDM and Topp et. al 1980

One can see in Figure 1 that the SMDM significantly overestimates the real part over the range of water content tested for the sand sample. For the sandy silt sample, the errors of the overall predictions have greatly reduced, but below approximately 20% water content the differences between the measured and predicted real dielectric constant are larger compared to the errors corresponding to the higher water contents. With the silty clay sample, SMDM predictions for the real dielectric constant are in good agreement with the measured data. Moreover, considering samples with dry density larger than 1.4 g/cm^3 and water content above approximately 25%, the performance of the model is relatively better compared to the remainder of the data.

For the sand sample, the Toop correlation performs with considerably smaller errors below 10% water content. However, the real part of the dielectric constant deviates from the measurements at higher water contents and is underestimated. With the sandy silt sample, the performance of the Topp correlation has improved significantly, however, the real dielectric constants are generally underestimated especially for samples with dry densities less than 1.9 g/cm^3. Conversely, for dry densities greater than 1.9 g/cm^3 and water contents below 15% the Topp correlation performs reasonably well. For the silty clay sample, Topp predicts the real dielectric constant with a reasonable agreement with relatively small errors for samples with dry densities greater than 1.4 g/cm^3. Nonetheless, for samples with lower dry densities, Topp underestimates the real dielectric constant. A similar performance of Topp correlation was reported in Dirksen and Dasberg (1993) for samples with dry densities greater than 1.3 g/cm^3 where it was found that Topp underestimated the real dielectric constant.

3.3 *Real dielectric constant versus dry density*

As explained earlier in the sample preparation section, through applying different compaction energies at constant gravimetric water contents, samples with different dry densities have been obtained. Furthermore, samples of similar volumetric contents have been regrouped to explicitly investigate the effect of compaction on the real dielectric constant of soil.

Figure 2 shows the change in the real dielectric constant at constant water contents (grouped at approximate 2% increments). In an attempt to explain these results, one must first recognize that water in soil can exhibit in terms of bound and free water. It is suggested by Dobson et al. (1985) that as the dry density increases, the volumetric bound water increases as:

$$\theta_b = \delta \cdot \rho_b \cdot A_s \qquad (10)$$

where θ_b is the volumetric bound water content; δ is the thickness of the water molecule attached to the solid particles (~9Å); ρ_b is the dry bulk density (g/cm^3); and A_s is the Specific Surface Area (m^2/g).

The higher A_s, the higher the ability of the soil solid particles to attract water molecules. Hence, at a constant volumetric water content, soils with higher A_s contain more bound water molecules than free water. A proportional trend between dry density and real dielectric constant has been repeatedly reported in the literature, and it has been suggested that through increasing the dry density, more solid particles are being introduced into the matrix and it is assumed that overall real dielectric constant of the matrix will increase accordingly. However, Equation 10 suggests that the effect of surface area also needs to be taken into account. By increasing the dry density of the matrix, for soils with high A_s, the amount of bound water starts to increase accordingly. Since bound water has a significantly lower dielectric constant compared to free water, it is hypothesised that for soils with certain A_s, the effect of density on real dielectric constant is inversely proportional.

In view of the above, the sand sample is first to be examined. The range of densities achieved with the aforementioned method for this sample is from 1.53 g/cm^3 to 2.13 g/cm^3 and the volumetric water content varies between 4.1% and 24%. The tested sand comprises of 97% sand and 3% silt. The A_s associated with the sand is very small compared to the other two samples, hence, it is suggested that the volume of bound water relative to the total volumetric water content is considerably low within this soil matrix. Thus, different compaction energies are not expected to change the proportion of bound to free water significantly and variations are expected to be subtle at a given volumetric water content. It is not expected therefore to find any inversely proportional trend between density and the real dielectric constant for this sample. Thus, as the dry density increases at constant water content (in the absence of the bound water state) and more air voids are being taken up by solid particles, it is expected to see an increase in the total dielectric constant of the matrix. This is due to the larger real dielectric constant of solid particles compared to air (i.e., $\kappa'_{\text{solid}} = 4.7 > \kappa'_{\text{air}} = 1$).

As Figure 2 shows, for the sand sample, the real component changes proportionally with dry density, however, insignificantly for samples with water content below approximately 15% (zone A). Nevertheless, while approaching the optimum volumetric water content (approximately 20% for this soil), a more obvious increasing trend can be observed (zone B).

For the sandy silt sample, the sensitivity of dielectric constant to the dry density is expected to be larger due to its higher A_s. It can be seen in Figure 2 that the variation of real dielectric constant for a change in dry density from 1.64 g/cm^3 to 2.03 g/cm^3 is indeed more significant for this sample over the previous sand sample.

Moreover, the water content has changed from approximately 8% to 31%. At lower volumetric water contents (i.e., below 10%), the effect of dry density on the real component of dielectric constant is minimal (zone A).

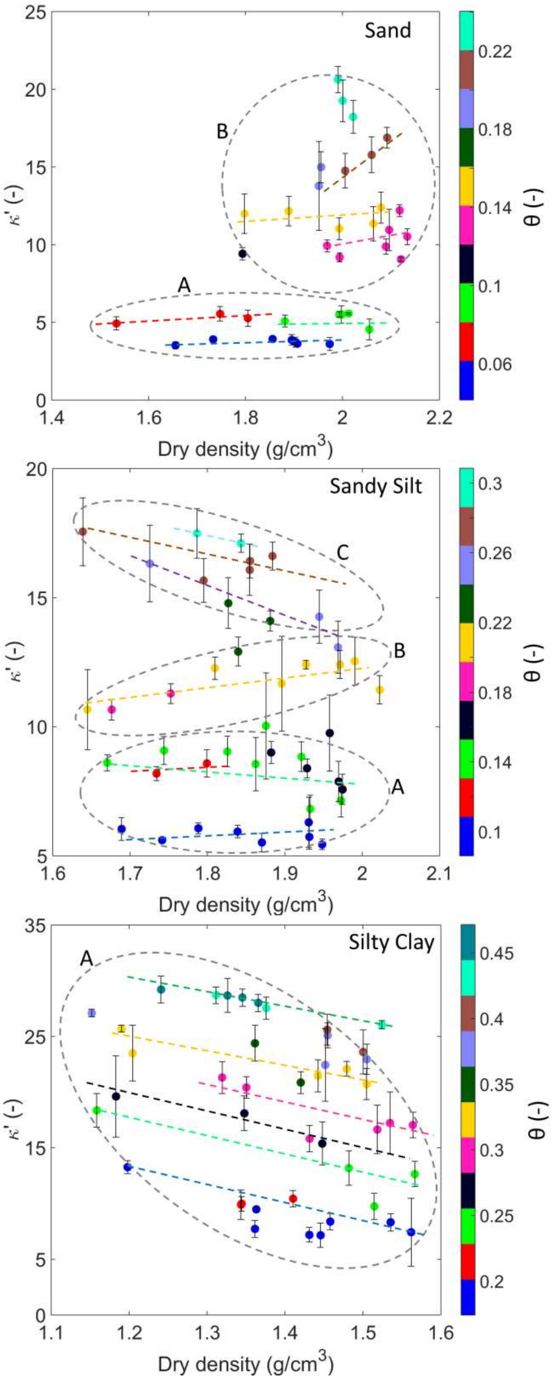

Figure 2. Effect of density on the real dielectric constant (1 GHz) at constant water content (dotted lines to guide the eye)

There is no significant variation for the real dielectric constant against dry density for low water content samples, however, as the volumetric water content increases to approximately 20%, a proportional trend is observed. Still, as the volumetric water content increases above 20% (Zone C), there can be seen an inversely proportional trend between the dry density and the real dielectric constant due to the increase in the number of bound water molecules with increasing dry density.

Lastly, for the silty clay sample, the ranges of variation of water content and dry density are 1.15 g/cm^3 to 1.57 g/cm^3 and 17% to 47% respectively. Different compaction energies have been applied to the clay samples starting from a moist condition, hence, the effect of dry density on the dielectric properties of clay particle below 20% volumetric water content could not be investigated. As Figure 2 shows, there is a clear negative trend between dry density and the real dielectric constant (zone A) for the tested water content range. This behaviour is attributed to the increase in the number of bound water molecules as the dry density increases at a given water content (Equation 10). This effect is dominant over the water content range and more obvious for this soil sample due to the significantly larger specific surface area (see Table 1.)

4 IMPROVEMENT TO THE SMDM MODEL

Based on the preceding experimental results and the discussions, an improvement is suggested to the SMDM model which focuses on the textural coefficient β'. The values for the soil texture coefficient β' were optimised and the following equation is suggested:

$$\beta' = 1.2695 - 0.00279\,Sand\% - 0.00288\,Clay\% \qquad (11)$$

Based on this improved equation, results of the predictions using the improved SMDM model are presented in Figure 3 (as MSMDM).

The predictions of real dielectric constant using the modified model improved significantly for the sand and slightly for the sandy silt sample. Conversely, for the silty clay sample, the performance of the model is improved only for samples with dry density below 1.4 (g/cm^3), however, the errors are larger for samples with higher densities. Further modifications could be implemented to the SMDM model to capture the effect of specific surface area and dry density.

5 CONCLUSION

This study investigated the effect of soil geotechnical parameters on the real dielectric constant of soil samples from 3 different geological formations from Melbourne (Australia). Proportional trends between volumetric water content and real dielectric constant have been observed and are soil type dependent. Although the overall trends observed from experimental data follow the trends predicted by the SMDM model and Topp correlation, discrepancies were observed. The discrepancies seem to be attributed to the limitations of the models in capturing the effects of texture and dry density. Additionally, the empirical correlations are generally based on the original conditions on which they were originally derived upon and might not properly capture other soils/conditions.

An improvement to the SMDM model has been suggested for soils with no to low plasticity.

More importantly, it was found (and hypothesised) that for soils with high Specific Surface Area, density can exhibit an inversely proportional relationship with the real dielectric constant. This effect has only been briefly mentioned in a very limited number of other studies.

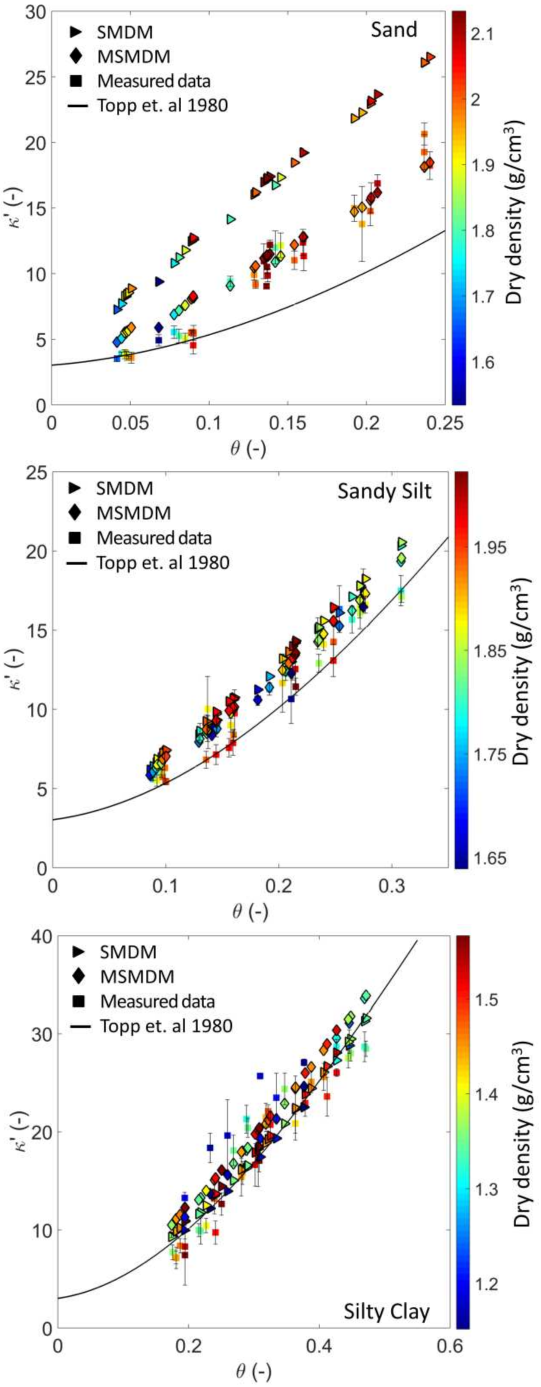

Figure 3. Predicted real dielectric constant at 1 GHz compared against, measured data, SMDM and Topp et. al 1980.

6 ACKNOWLEDGMENTS

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