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Frequency dependent electric properties of homogeneous multi-phase lossy media in the ground-penetrating radar frequency range

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ABSTRACT

The electric properties of multiphase aggregate mixtures are evaluated for a given mineralogic composition at frequencies between 300 kHz and 3 GHz. Two measurement techniques are employed: a coaxial transmission line and a monostatic stepped-frequency ground-penetrating radar (GPR). The effect of increasing water content is analyzed in several sand clay mixtures. For the end-member case of maximum clay (25% in weight) and increasing water content, investigations are compared between the two measurement techniques. The electrical properties of materials are influenced by the amount of water, but clay affects the frequency dependency of soils showing distinctive features regardless of the mineralogy. The microwave attenuation, expressed by the quality factor Q, is partly dependent on frequency and on the water content. The performance of one empirical and one volumetric mixing model is evaluated to assess the capability of indirectly retrieving the volumetric water content for a known mixture. The results are encouraging for applications in the field of pavement engineering with the aim of clay detection. The models used show similar behaviors, but measured data are better modeled using third order polynomial equations.

1. Introduction

Non-destructive characterization of road pavement layers is crucial for the life, safety, and maintenance of infrastructures (Tighe et al., 2000). Road maintenance can incur considerable direct and indirect costs (Benedetto and Pensa, 2007), which has led to comprehensive cost-benefit assessments. Geophysics has been used to evaluate pavement conditions and to assess potential or existing damages. In particular, it is widely recognized that ground-penetrating radar (GPR) is a valuable tool for non-destructive road inspection and condition monitoring (Jol, 2009; Loizos and Plati, 2007).

Considerable efforts went into the evaluation of concrete and asphalt thickness (Saarenketo and Scullion, 2000; Spagnolini and Rampa, 1999), reinforced concrete bridge decks deterioration (Hugenschmidt and Mastrangelo, 2006), and subsurface soil investigations. Recent research focusedon the detection of damages in the asphalt layers, recognizing that the origin of instabilities might be due to the subgrade soil behavior (Diamanti and Redman, 2012).

Research was conducted to accurately determine and model the electric properties of soil multi-phase mixtures in the microwave region (Dobson et al., 1985; Hallikainen et al., 1985). A review of the existing petrophysical models for GPR frequencies is given by Steelman and Endres (2011). (Saarenketo, 1998 measured the electric properties of soils at different densities and water contents at given GPR frequencies; they classified water in soils according to the electrical behavior, as being adsorbed, viscous, or in a free state. The frequency dependency of adsorption and dispersion in lossy media was studied by Bano (2004) using the quality factor Q and a complex power function with the aim of modeling the electric behavior of materials.

Despite the accuracy of the results shown in literature for multi-phase mixtures, little attention has been given to the ability to detect clay independently from water content in subgrade soils. A study that combines GPR full-waveform inversion and dielectric mixing models was carried out by Tran et al. (2012). However, full-waveform inversion results have not yet been compared with reliable ground-truth measurements for sand clay mixtures. The frequency dependency of the electric parameters has been thoroughly investigated (Gregoire and Hollender, 2004; Lambot et al., 2005), but exact measurements and comparisons in the GPR frequency range for multi-phase mixtures are still missing.

In this paper, the influence of clay on the electric properties frequency dependency, usually neglected or considered in a relatively narrow-band, is properly highlighted for different water content mixtures. Topp's model (Topp et al., 1980) is used to assess whether the presence of clay limits the capability to determine water content.

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Table 1
Physical properties of the materials used. Ranges of values are given for parameters determined over different water content samples. The symbol γ indicates the specific weight in natural conditions (subscript n), in dry conditions (dry) or in saturated conditions (sat); ε_r indicates the real electric permittivity and θ_v% the volumetric water content.

	γ_n (g cm^{-3})	γ_{dry} (g cm^{-3})	γ_{sat} (g cm^{-3})	Porosity	ε_r	θ_v %	Saturation %
Sand *A2*	1.58–1.94	1.45–1.54	2.66	0.40	2.6–2.9	0–0.39	0–94
Sand *A3*	1.39–1.78	1.33–1.39	2.66	0.36	2.5–2.8	0–0.39	0–86
Clay –	1.71	–	2.41	–	2.98–10.0	–	–

A volumetric mixing model (Birchak et al., 1974) is tested and extended from two to three-phase simple cases to four-phase mixtures. Measurements are performed using a stepped-frequency GPR on natural size samples, in an effort to extend this approach to field-scale measurements. Results show the possibility to relate water and clay contents to the electric properties, eventually via the quality factor Q. The effect of bound water can be hypothesized both from the transmission line and GPR results.

2. Techniques

The frequency dependent complex electric permittivity $\varepsilon_r^* = \Re(\varepsilon_r) + J\Im(\varepsilon_r)$ is measured using a coaxial transmission line and a monostatic off-ground stepped-frequency radar. The relative electric permittivity $\varepsilon_r = \varepsilon/\varepsilon_0$ is the ratio between the electric permittivity ε and the free space electric permittivity $\varepsilon_0 = 8.854 \times 10^{-12}$ Fm^{-1}. For both setups a HP Vector Network Analyzer (VNA) 8753C is used together with a HP S-Parameter test set 85046A, connected to a horn antenna with a 50 Ω impedance coaxial cable in the case of GPR, or to the transmission line end points. The frequency bandwidth used in the transmission line setup and in the GPR are 300 kHz–3 GHz, and 500 MHz– 3 GHz, respectively. The antenna used in the GPR setup is a double-ridged broadband horn (BBHA9120A, Schwarzbeck Mess-Elektronik).

The complex relative electrical permittivity is computed from an explicit expression that relies on the transmission line measured scattering parameters using the propagation matrices method (Thomson, 1950); the adaptation of this method to the EM case is based on an analytical solution and is described in details in Gorriti and Slob (2005a).

For a single transverse electromagnetic (TEM) horn antenna connected to a VNA and illuminating the earth in the far field, a known radar antenna mathematical model (Lambot et al., 2004) allows to retrieve the earth impulse response from the reflection data. A detailed description of the system calibration technique and inversion procedure can be found in Lambot et al. (2004). Different samples' preparation techniques are used, as explained in Section 1.

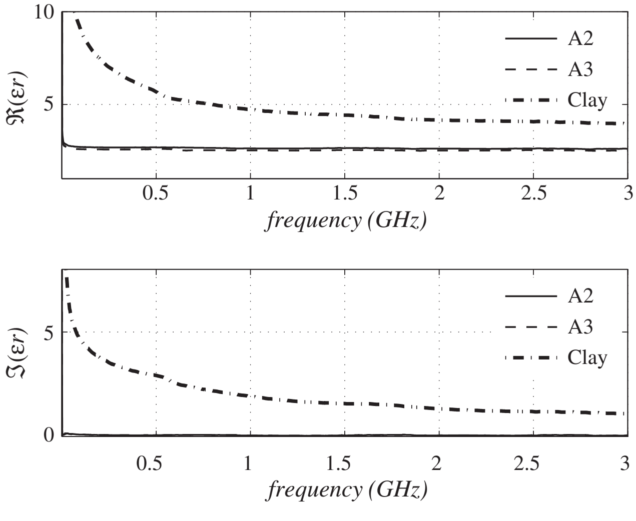

Fig. 1. Real and imaginary part of the ε_r measured for *A2*, *A3* sands and clay over the entire frequency range.

2.1. Materials and experimental procedure

The experiments described are conducted in a temperature controlled laboratory environment, at 20 °C ± 2°. Two different sand grain sizes are used: a 1.00–2.00 mm and a 0.125–0.250 mm, hereafter named, respectively, *A2* and *A3*; a distinction is made only based on the particle-size distribution according to the AASHTO soil classification (AASHTO, 2011). Some physical properties of the material used are given in Table 1.

2.1.1. Transmission line

The measured electric parameters are functions of the relative abundance of the constituents present in the mixtures and of their relative electric properties. The analyzed components are two different mineralogy sands, bentonite clay, water and air. To evaluate the effect of water and clay content on EM signals the following variables are considered:

- clay content: from 0%$_w$ to 25%$_w$ using steps of 5% increase in weight in dry conditions;
- water saturation: from oven-dry to 30%$_w$ water content (above 90% saturation) using non-linearly increasing steps for a given mixture.

A total of 78 measurements of the electric properties were performed for each sand as a function of frequency. Fully-saturated samples are prepared for the two sands *A2* and *A3*.

Calculated amounts of water with a conductivity of 508 μS/cm were used to reach the desired moisture; manual mixing followed until a homogeneous mix was obtained. The volumetric content of all phases is known since the densities of the single phases were measured with a gas pycnometer (Tosti et al., 2013–this issue); the transmission line sample holder volume is known, as well as the GPR sample containers. The actual water content is determined gravimetrically using the entire sample after measurements. The samples' natural volume weight, indicated as γ_n (g/cm^3), is determined before and after measurements; the difference was always less than 1.5%, confirming a limited loss of material and water evaporation during measurements (15 minutes).

2.1.2. Ground-penetrating radar

In GPR measurements the end-member conditions for maximum clay content was varied:

- saturation: from oven-dry to 25%$_w$ water content using non-linearly increasing steps.

Soil mixtures are placed into a dedicated container for measurements; the GPR measurements are a larger scale analogue of the experiments described in Section 1. The container is PVC made, 10.5× 40 × 47 cm^3 in size; this lays on a 1.5 × 1.5 m^2 perfect electric conductor (PEC) plate used to control electric bottom boundary conditions. The size of the box is chosen such that the penetration depth is satisfactory and is comparable to what is realistically achievable on the site. Necessary