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MICROWAVE DIELECTRIC SENSING OF MOISTURE IN MSWI-BOTTOM ASH – COMPARISON OF FREQUENCY VS. TIME DOMAIN REFLECTOMETRY

Fukthaltsmätning i bottenaska med dielektriska metoder – en jämförelse mellan mätningar i tids- och frekvensdomän

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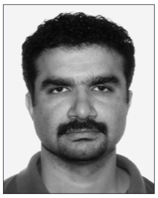

Abstract

This paper presents the detection of moisture content in municipal solid waste incineration bottom ash (MSWI BA) with two different measurement techniques. The study used a frequency domain coaxial probe and a short TDR probe to evaluate and compare the performance of the both probes for lossy materials. Instead of using complex data conversion algorithms, between the two domains, the study directly compared the results measured in time and frequency domain as a function of water content. The samples of BA were prepared at four different volumetric water contents (0.10, 0.20, 0.30, and 0.40 $m^3\ m^{-3}$) and the measurements were made without varying the bulk densities. The results were analysed with principle component analysis (PCA) to highlight the variable groupings and differences among the techniques. The results showed that frequency domain method was better for moisture estimation in lossy materials such as BA. The TDR under predicted the water content under similar experimental conditions and its performance reduced with the increasing salinities and water contents. Thus, it was concluded that FDR measurements between 300 MHz and 1.5 GHz were suitable for moisture content detection in lossy materials.

Key words – Bottom Ash, TDR, FDR, Microwaves, Moisture, Salinity, PCA

Sammanfattning

Denna artikel handlar om fukthaltsmätning i bottenaska (BA) från förbränning av hushållsavfall. Två mätmetoder jämfördes, frekvensdomän- och tidsdomänreflektometri (FDR och TDR). I studien jämförs korrelationer mellan rådata och fukthalt, utan att gå via komplicerade kalibreringsmodeller. Detta för att se vilken metod som har bäst potential för fukthaltsmätning. BA-prover med vattenhalter på 0.10, 0.20, 0.30, and 0.40 $m^3\ m^{-3}$ blandades till samma bulkdensitet. Resultaten analyserades med *principle component analysis* (PCA). Resultaten visade att FDR var den bättre metoden av de två, TDR-metoden underskattade vattenhalterna, särskilt vid högre elektrisk konduktivitet. FDR-metoden vid frekvenser mellan 300 MHz och 1.5 GHz var bäst lämpade för fukthaltsmätning i BA.

Introduction

Bottom ash (BA) is a by-product of energy recovery from municipal solid waste. The proposed strategy for BA's management is to reuse it as a construction material. Despite having excellent geotechnical characteristic, the BA is enriched in metals, salts, minerals, glassy phases and residual organics. Therefore monitoring and control of the pollutant transport from BA reuse sites is of paramount importance. The emission of pollutants (through the leaching process), to soil and ground water, depends on volumetric, temporal and spatial variability of moisture inside the BA. To determine the moisture variability over entire length or breadth of a construction, such as a road, is not an easy task. Laboratory methods which require digging the sample cores are impractical as invasive sampling reduces the stability of construction and fails to capture the variability. Even if one were allowed to dig samples out of a road, the sheer number of samples needed for a representative moisture value would render the entire exercise costly and time consuming. Moreover, under the current regime of dry landfill, proposed by EU, controlling the moisture would be a critical factor in achieving the objective of zero leachate emissions. Therefore, in this context, rapid and non-destructive measurement techniques would be needed for real time assessment leaching risks from BA reuse sites and monitoring of infiltration fronts in the landfills.

The detection of moisture in waste materials such as BA, however, presents a special challenge due to high amounts of electrolytes. In any non-invasive application of moisture detection, the presence of electrolytes, in material under test (MUT), is often a complicating factor. The salts and other ionic solutes impart an electrical conductivity to solutions and particulate samples which reduces the accuracy of the measurements. The majority of the currently available methods rely on the travel time analysis, where an electromagnetic (EM) pulse is sent in the MUT and the time of travel is measured to estimate the dielectric property such as the dielectric permittivity. The dielectric permittivity is then related to water content of the samples through empirical or physical dielectric mixing models. Among these techniques, the TDR (Topp et al., 1980) is widely used in moisture content detection. The TDR can estimate electrical conductivity simultaneously with water content (Lin et al., 2007). However, the TDR, developed for agricultural soils, is not suitable for application on waste materials. Even at moderate salt concentrations e.g. 2 dSm^{-1}, the loss of the TDR signal drastically lowers its ability to determine the water content (Jones and Or, 2004). One solution is to transform the signals through Fourier transforms into frequency domain (e.g. Heimovara, 1994; 1996; Jones and Or, 2004). This kind of transformations, however, militates against the logic of rapid detection as these calculations increase the analysis time.

An alternative solution is to use shorter TDR probes or techniques based in frequency domain (FD). The FD techniques instead of measuring the travel time estimate the parameters such as amplitude and phase, of the reflected EM, which are not susceptible to electrolytes. In the FD techniques, the frequency range can be fixed a priori which is beneficial in determining the suitable frequency range for measurements. In contrast, the TDR uses a broad, but unknown, frequency range which can vary with each measurement and material. Therefore, the effective measurement frequency of TDR may not be static and repeatability of the measurement could be an issue. Previously, the FD techniques, relying on the coaxial probes, have been used in material testing, food industry and in biomedical applications. However, no such studies have been done to evaluate the effectiveness of the frequency domain reflectometery for the measurement of moisture in the waste materials such as BA. Nor has the results of FDR been compared with shorter TDR probes.

The objective of this paper was to measure moisture content in BA samples in the laboratory with both FD technique, referred to as FDR, and short TDR probes. Heimovaara et al. (1996) did a comparative analysis of TDR and FDR, however their approach was to transform FDR into time domain with help of an inverse Fourier transform and then compare the wave forms. In contrast, our approach is rather direct which compares measured permittivity as a function of volumetric water. Thus, in this way the need for complex computational routines for data conversion from one domain to another was avoided. This is a straightforward procedure since the sample volumes, water content and BD were same in both instances of the measurement, and therefore, any effects of these could be ignored.

Background Theory

Both frequency and time domains are two sides of a same proverbial coin. Usually in scientific experimentation or data collection, the data are collected over time (e.g. water flow, rainfall, temperature, pollutant concentrations etc.) therefore the time domain is more visible. The frequency domain, in contrasts, exists like a hidden dimension or shadow of time domain. The transfer to frequency domain is achieved through transformation of time domain data through Fourier transforms and vice versa.

Frequency Domain Reflectometry

The FDR measures amplitude (dB) and phase (degrees) of the reflected pulse at each frequency window. In the current configuration using a coaxial probe, the FDR measures the reflection coefficient at the probe aperture which is then related to permittivity through either a lumped circuit model or variational techniques (see Blackham and Pollard, 1997; Stuchly et al., 1974). The permittivity, in FD, is a complex function since it measures one real quantity (amplitude) and one imaginary (phase). Therefore, the dielectric permittivity is referred to as complex permittivity (Eq. 1). Although EM pulse

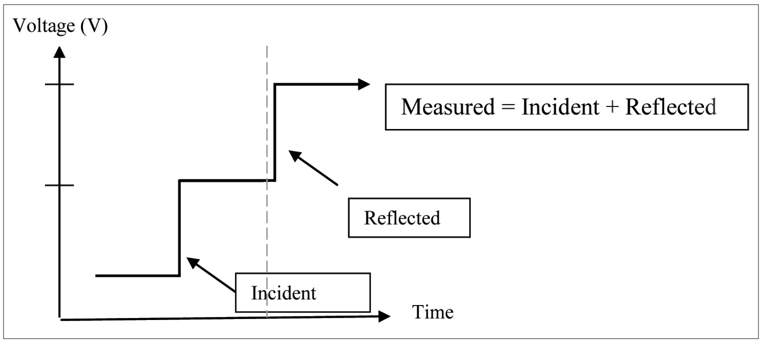

Figure 1. *Illustration of TDR pulse and different measurement points.*

generates both electrical and magnetic fields, however the magnetic component of the electrical field is ignored for non-magnetic materials.

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \quad (1)$$

Where ε^* is complex permittivity, ε' is the real part indicating the energy storage, ε'' is the imaginary part indicating the energy loss and j is the complex coefficient. For the practical purpose of our measurement, ε' is related to water content and it would be compared with the permittivity measured by TDR at each water content.

Time domain Reflectometry

The TDR uses the travel time analysis (TTA) where the velocity of EM through the probe (Eq. 2) and propagation velocity through the material are computed (Eq. 3). The propagation velocity (v_P) through the material is a ratio between the velocity of the EM in the probe (v) and the velocity of the EM in free space (c). Then the v_P, through Eq. 4, is related to the dielectric permittivity of the material.

$$v = 2L/t \quad (2)$$

$$v_P = 2L/ct \quad (3)$$

$$1/\sqrt{\varepsilon_r} = 2L/ct \quad \text{or } \varepsilon_r = (ct/2L)^2 \quad (4)$$

Where v is velocity (m s^{-1}), L is length of probe (m), t is time (s), c is velocity in free space, and ε_r is relative permittivity of the material. Figure (1) illustrates the TDR pulses reflections and measurement points.

As seen from figure 1, the TDR reflections are shaped as rising steps which essentially rely on applied voltage (V) by the instrument. Therefore for TDR to avoid conductivity effects it either has to increase the voltage or rely on shorter probes which would reduce the travel path to allow reflections. Increasing the voltage is not option since it would result in exorbitant cost for the instruments and perhaps render TDR unsuitable for field application. Therefore, using shorter probes would be far more economical, although shorter probes would also reduce the measuring volume. Nevertheless, for laboratory study where smaller samples volumes are used, the shorter probes are suitable. For samples of larger volumes or field scale analysis, it would be more practical to coat TDR probe with plastic to offset conductivity effects.

Figure 2 illustrates the difference in measurement methods of the two techniques. Both of them measure the dielectric permittivity which is related to the water content of the materials. In case of FDR the loss of electrical signal is directly expressed as conductivity (through ε'') which is an advantage over TDR. The imaginary part is related to the conductivity by Eq. 5 thus it can be used to calculate the bulk of effective conductivity of the samples.

$$\sigma = \varepsilon''\varepsilon_0 2\pi f \quad (5)$$

Where σ is conductivity S/m, $2\pi f$ is angular frequency rad/s and ε_0 is the dielectric permittivity of free space.

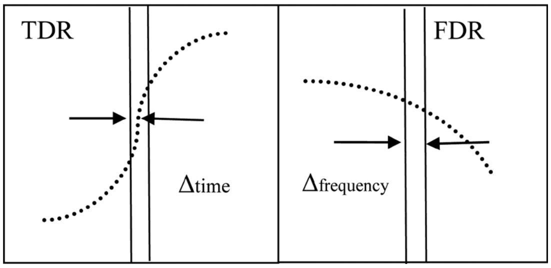

Figure 2. *Differences in measurement principle of TDR and FDR. First part of the figure shows TDR and second shows FDR.*

Materials and Methods

Sampling and Measurement Setup

The BA, obtained from a local MSWI plant, was used for testing the moisture content with FDR and TDR. The ash particle fraction below 1 mm was used because it provides most of the water holding capacity. As a reference material, sand samples were also used in the study. The use of sand was due to its neutral properties thus it helped highlight the effect of salts addition. The samples were oven dried at 105 ºC for 24 h prior to the measurements. Deionized water and two different NaCl solutions with electrical conductivities of 10 and 20 dS m^{-1} were used to prepare the water contents ranging from 0.1 to 0.4 $m^3\ m^{-3}$ in 0.1 $m^3\ m^{-3}$ increments, resulting in a total of 16 samples. The measurement setup for frequency domain included a network analyzer, a dielectric probe and the dielectric software for data acquisition. The TDR system consisted of an oscilloscope, a short probe and a 50 ohm cable. The measurements were done in the same sample alternatively by TDR and FDR. The measurements were made immediately after the mixing and in short succession in order to avoid moisture losses from the samples through evaporation.

Multivariate Data Analysis

Principle component analysis (PCA) was performed on the data matrix comprising TDR and FDR measurements at various water content and salinity levels of BA and sand samples. The PCA can be performed by either Eigen value decomposition of co-variance matrix or singular value decomposition of a normalized and mean centered data matrix (Wilks, 2006). The PCA provides a tool to reduce the dimensionality of the data by calculating the orthogonal principle components with first PC explaining most of the variance. From this standpoint, the FDR data is suited for such analysis since 51 frequency points with several water contents and salinity levels would mean that all the data cannot be represented on a single axis.

Results and Discussion

The dielectric permittivity represents the energy storage in a sample which is related to water content (figure 3). Over all the permitivity varied between 2 to 42 over a volumetric water content range of 0–0.4 $m^3\ m^{-3}$. The TDR gives similar estimates of permittivity at low water contents (< 0.15 $m^3\ m^{-3}$) but at higher water contents it starts to overestimate the permittivity. This shows that at higher water contents, due to the greater dissolution of salts, the effective frequency of TDR dropped below the 0.3 GHz. Robinson et al. (2007) have reported that the effective frequency range of TDR is between 0.7 to

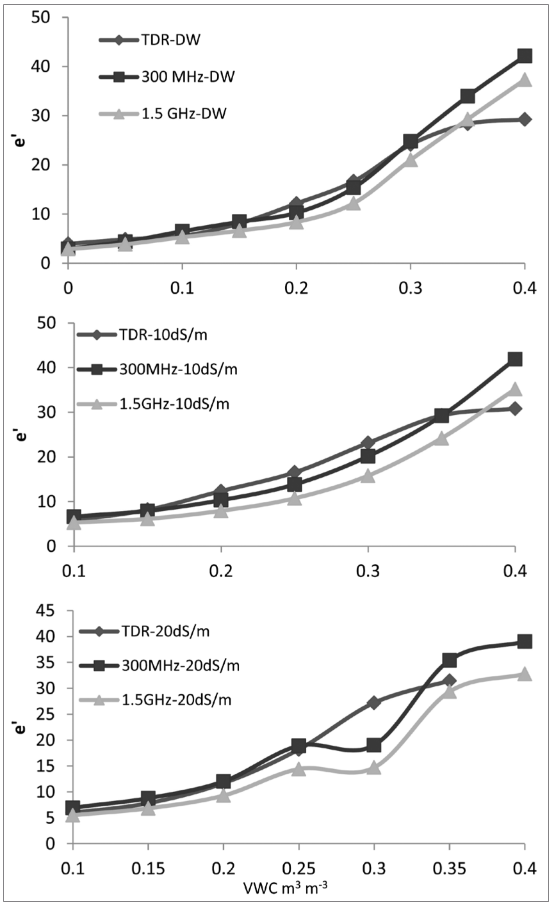

Figure 3. *Comparison of FDR and TDR at three different salinities. The FDR measurements are given for two frequencies 300 MHz and 1.5 GHz.*

1 GHz for low loss materials but for lossy materials this can drop below 0.6 GHz. The release of water bound to particles could also affect the TDR measurement. Wraith and Or, (1999) have reported that the soil bulk dielectric permittivity measured by TDR was sensitive to the ratio of bound to bulk water content in soils. In contrast to TDR, the FDR measurements both at 0.3 and 1.5 GHz are consistent and only respond to changes in measurement frequency. The permittivity is lower at higher frequencies because the penetration depth decreases. This is plausible as higher frequencies have shorter wavelengths, which means lower penetration depth. Moreover, from the figure it is also obvious that FRD measurements were consistent even with increasing salinity and the TDR at highest salinity of 20 dS/m and water content couldn't measurement the permittivity. The variation in FDR in the same figure could be due to matrix effects or due to contact problems.

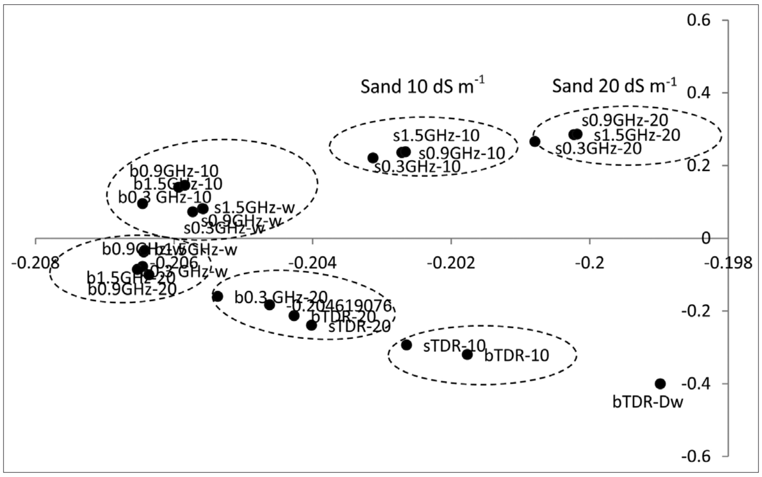

Figure 4. *Loading plot of PC1 and PC2 of original data matrix (explained variance 98 %).*

The results of the PCA (Figure 4) are presented as a plot of PC1 and PC2 both of which explain most of the variance in data. From the results it is clear that the FDR measurements are separated from TDR in space and in materials. The PCA, by grouping together the similar variables, highlights the underlying relationship among TDR and FDR data. In case of FDR the measurements are consistent and grouped on the basis of frequency, salinity level as well as the type of material.

In case of TDR, the measurements do not follow any grouping except the measurements at 20 dS m^{-1} which are close to FDR measurement with distilled water at 0.3 GHz. This indicates that TDR was underestimating the moisture content at higher salinities and its effective measurement frequency was perhaps close to the lower end of FDR frequency (0.3 MHz). The same trend can be observed in TDR measurements on sand and BA at 10 dS m^{-1}.

Conclusions

The study compared two different techniques for moisture estimation in samples of bottom ash. The results demonstrate that the shorter TDR can avoid the problem of signal loss in relatively high conductivity samples but only up to a certain salinity level. However at higher water content salinities, 10 and 20 dS m^{-1}, the TDR probe could not predict water content. The results also highlighted that FDR measurements are less affected by salinity than TDR. In comparison FDR performed better and provided consistent measurement of water content under different conditions. Further, the use of PCA was highly effective in discerning the under lying difference and relationship in the data set. More work on BA samples at field scale and using coated probes is suggested.

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