

## Slutrapport för projektet ”Övervakning av urlakning från förbränningsrestprodukter”

För finansiering av detta projekt söktes 750 kkr varav 300 kkr var erhöles vardera från J. Gust. Richerts Minne och Ångpanneföreningens Forskningsstiftelse. Projektarbetet startades under hösten 2008 och avslutades i maj 2010. Personer som direkt har varit inblandade är Professor Magnus Persson och doktorand Aamir Ilyas från Teknisk vattenresurslära vid LTH och Tekn. Dr. Martijn van Praagh, SWECO.

### Mätningar

Ett stort antal mätningar har utförts. Några olika material har testats, bottenaska, slaggrus och ett järnoxidrikt industrislag. Både färskt och lagrat material har använts. I en nära framtid skall även flygaska testas med samma metodik. I ett första steg har vi försökt utröna hur vattenhalten i materialet kan uppskattas med hjälp av den dielektriska permittiviteten och hur vattenhaltsmätningen påverkas av den elektriska konduktiviteten. Askor har blandats med vatten med olika elektrisk konduktivitet. Vattenhalten har varierats från 0 till  $0.4 \text{ m}^3 \text{ m}^{-3}$  i steg om  $0.05 \text{ m}^3 \text{ m}^{-3}$ . Mätningar har skett både i frekvensdomän (FDR) och tidsdomän (TDR). För mätning i frekvensdomän har en ENA-5061A (Agilent Technologies USA) använts med en dielectric probe (Agilent, 85070E). För TDR mätningarna användes en Tektronix 1502 C tillsammans med en 4 cm lång mätprob.

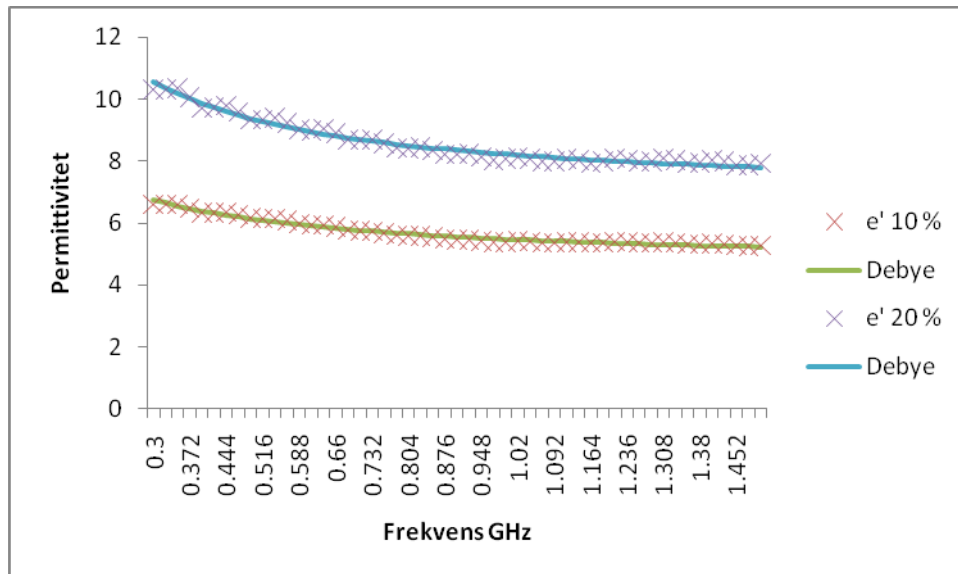
Nästa steg var att mäta vad som händer i ett askprov under urlakning. En FDR mätprob monterades i ett litet prov med färsk aska som urlakades under en vecka med ett konstant vattenflöde. Provet var mättat med vatten under hela detta försök, vattenhalten var således konstant.

### Resultat

Resultaten visar att FDR är en säkrare metod för vattenhaltsmätning eftersom den påverkas mindre av hög elektrisk konduktivitet än TDR. För mer detaljerade resultat se de Ilyas et al (2009; 2010a; 2010b). Däremot visade sig FDR metoden som användes i denna studie vara väldigt känslig för att ha perfekt kontakt mellan mätproben och askan. Detta gör att metoden för närvarande endast lämpar sig för välkontrollerade laboratorieförsök. För att göra metoden mindre känslig bör en annorlunda mätprob baserad på transmission istället för reflektion användas, vilket väsentligt kommer att öka den effektiva mätvolymen.

Vid långtidsmätningar i askor under urlakning kommer den elektriska konduktiviteten att sjunka över tiden, denna förändring måste man kunna korrigera för om man vill få exakta fuktmetningar. Detta har vi löst med dielektrisk modellering, där hänsyn tas både till reell och imaginär permittivitet. Vi använde en modell kallad Debye, som visade sig passa våra data utomordentligt väl (se Fig. 1). Parametrarna i modellen är funktioner av vattenhalt och därmed kan vattenhalten bestämmas för en mätning av den dielektriska permittiviteten i frekvensdomän.

Försöket med urlakningen visade på en minskande elektrisk konduktivitet över tiden. Försöket fick dessvärre avbrytas efter en vecka på grund av att mätproben förlorade kontakt med materialet, antagligen som följd av inre erosion. I framtida försök måste därför materialet packas bättre runt själva mätproben. Alla resultat från detta försök är för närvarande inte analyserade, detta förväntas göras under hösten 2010.



Figur 1. Dielektrisk permittivitet ( $\epsilon'$ ) mätt vid 10 och 20 % fukthalt samt modellerade värden med Debye-modellen.

### Publikationer

På basis av våra erhållna resultat har två konferensbidrag skickats in. Den första konferensen var Sardinia 2009. Denna hålls vartannat år och är alltid väldigt välbesökt. Senaste gången den hölls kom ca 1000 deltagare från 80 länder. Vi har också skickat ett abstract till Sixth Intercontinental Landfill Research Symposium” som hålls i Hokkaido, Japan 9-11 juni 2010. Båda dessa bifogas nedan. Ett längre manuskript till en vetenskaplig artikel har också skrivits, men detta är inte färdigställt ännu. Utöver dessa har även data samlats in till underlag för ytterligare en artikel som kommer att skrivas under hösten 2010.

### Bilagor

- Ilyas, A., Persson, M., v. Praagh, M. 2009. Measurements of moisture content of waste materials with frequency domain reflectometry (FDR). Twelfth International Waste Management and Landfill Symposium 5 - 9 October 2009, Sardinia, Italy.
- Ilyas, A., Persson, M., v. Praagh, M. 2010a. Microwave dielectric sensing of moisture in municipal solid waste incinerator bottom ash (MSWI-BA). Sixth Intercontinental Landfill Research Symposium, Hokkaido, Japan 9-11 juni 2010.
- Ilyas, A., Persson M., v. Praagh, M. 2010b. Dielectric relaxation modeling of municipal solid waste incinerator bottom ash. (manuscript)

# **MEASUREMENT OF MOISTURE CONTENT OF WASTE MATERIALS WITH FREQUENCY DOMAIN REFLECTOMETRY(FDR).**

A.ILYAS\*, M. PERSSON\*, M.V. PRAAGH\*\*

\* *Water Resources Engineering, Lund University, Box 118, SE 221 00, Lund, Sweden.*

\*\* *SWECO Environment AB, P.O. Box 286, SE201 22, Malmö, Sweden.*

**SUMMARY:** Incineration of municipal solid waste (MSW) has resulted in large quantities of residues which can be recycled in roads and landfill covers provided the environmental concerns related to leaching of salts and metals can be mitigated. The pollutant transport from these residues depends on quantity and variability of moisture at re-use sites. For realistic assessment of leaching rates and pollutant transport risks quantifying the moisture variability is important. However due to destructive nature of traditional sampling regimes it is not possible to study moisture content of residues in the field. This study has tested a non invasive frequency domain based method at laboratory scale for its ability to measure moisture content in two different types of waste materials. The results show that despite high salt concentrations in waste samples this technique is robust and does not suffer from errors often encountered in time domain approaches.

## **1. INTRODUCTION**

Moisture is a key parameter in our understanding of leachate production, biodegradation and pollutant mobility from waste materials land filled or recycled. The current EU legislation (EC 99/31 is aimed at reduction of biodegradable wastes in landfills which means that the bulk of MSW has to be incinerated. This practice extracts energy from waste stream but also results in massive quantities of residues or ashes. The bottom ash which comprises major part of these residues has gravel and sand like particles. Therefore it is suitable for construction of roads, parking lots and landfill covers. In Sweden according to Ribbing (2007) approximately 1 million ton of bottom ash is produced per annum most of which is used in landfill covers and in roads-as sub-base layer. Main concerns related to re-use of bottom ash are leaching of metals, salts and organic contaminants to soil and ground water (Ore et al., 2007). According to current EU regulations bottom ash samples are tested in laboratory columns for determination of total content of pollutants. However, these laboratory columns can not simulate field scale flow velocities and physical non-equilibrium (Hyks et al., 2009). Moisture content controls several chemical processes such as hydrolysis, dissolution/precipitation, carbonation, oxidation/reduction, complexation, sorption, and as well as neo formation of minerals. The quantity and variability of moisture content in waste materials will also affect the physical pollutant transport processes. Therefore, for safe management of the residues, risk assessments must be based on measured moisture content in order to predict leaching of pollutants to surface and groundwater system.

Monitoring of moisture content variability in the field is not feasible via sampling regimes using destructive methods. The use of common electromagnetic (EM) techniques such as TDR and GPR may not be suitable due to presence of high amounts of salts in the bottom ash. These techniques rely on travel time analysis of EM pulses which can be error prone due to high electrical conductivity of the ashes. There is a need for a non invasive method of measurement which is suitable for dispersive waste materials such as bottom ash. Data from moisture content studies can help determine the hydraulic parameters which can be utilised for geochemical transport models to assess the soil and groundwater pollution risks.

Keeping in mind the afore mentioned issues, the specific objective of this study is to demonstrate the application of frequency domain approach (FDR) in measurement of moisture content in bottom ash. This is likely the first attempt to apply this technique on bottom ash. Previously, microwaves have been used in moisture content sensing in food laboratories and online food processing applications (see Kent, 2001). Most of the processed foods items have high ratios of electrolytes, sugars and fats which can cause dispersion. In this regards waste materials such as bottom ash, industrial sludge and organic contaminated soils exhibit similar dispersive behaviour. Therefore application of microwaves can provide a cost effective, non destructive and non invasive moisture sensing system for waste management industry.

## **2. MICROWAVES AND FDR**

Microwaves are pulses of electrical energy with frequencies between 300 MHz and 300 GHz. The interaction of microwaves with materials is defined by the characteristics of the material and by the frequency range used in the measurements. Behari (2005) provides an exhaustive review of methods and the results of microwave dielectric measurements in soils. The utility of microwaves, in moisture sensing, is based on their insensitivity to electrical conductivity and greater absorption by water molecules (Trabelsi and Nelson, 1998). The problem of electrical conductivity arises at radio frequencies (below 200 MHz) which are prone to dispersion and attenuation in dispersive materials. Microwaves have qualitatively different interaction with water than solids. Pure water has a much higher electrical permittivity (80) compared to solids and polar character of water molecules results in selective absorption of microwaves. The changes in chemical composition of water (i.e. addition of salts) hinder dipole rotation of water molecules and lower its relaxation frequency. This sensitivity of water to compositional changes and its absorptive capacity allows the use of microwaves for sensing moisture in solid materials.

The FDR method is based on reflection of electromagnetic (EM) pulse from the material under test (MUT). The term frequency domain here refers to the fact that electrical signal is represented as a function of frequency. The FDR uses an open ended coaxial cable of known resistance (50 ohm) to send electrical pulse into the MUT. Due to difference in impedances or resistances of cable and the material the EM pulse is reflected backwards. The magnitude of reflection depends on presence of water molecules and conductive solutes. From drier samples most of the electrical energy will be reflected backwards and thus the electrical permittivity of the material

will be low. While moist or saturated samples the EM energy is lost due to torque imparted by current to dipoles.

## 2.1 Dielectric permittivity

The dielectric permittivity (or relative permittivity) is the ability of solid material and also liquids to store electrical energy. When a solid sample is placed in an electrical field it gets polarised or charges align along the direction of field in order to balance the intrinsic electric field of the material. Table 1 gives permittivities of different minerals and reference fluids.

Table 1: Permittivities of minerals and reference fluids.

Material	Permittivity	Source
Air	1.0	Lucius et al., 1989
Calcite	6.4	Olhoeft, 1989
Calcite	7.8-8.5	Keller, 1989
Gypsum	6.5	Martinez and Byrnes, 1999
Halite	5.9	Olhoeft, 1989
Ice	3.4	Olhoeft, 1989
Kaolinite	11.8	Olhoeft, 1989
Mica	6.4	Martinez and Byrnes, 1999
Montmorillonite	210	Olhoeft, 1989
Olivine	7.2	Olhoeft, 1989
Orthoclase	5.6	Olhoeft, 1989
Quartz	4.5	Olhoeft, 1989
Water	80	Lucius et al., 1989

(Modified from Martinez and Byrnes, 2001)

In the absence of an electric field the charges relapse to their random orientation. However there is a time difference between orientation and relapse of charges which is called relaxation. During alignment process charges store electrical energy but some energy is lost in the form of heat during this relaxation (Robinson et al., 2003) or due to presence of salts. Therefore, dielectric permittivity ( $\epsilon$ ) is represented as complex function with real and imaginary components and is defined by equation [1] given below. The real part ( $\epsilon'$ ) of permittivity is the ratio of the electric-field storage capacity to that of free space (Powers, 1997). The imaginary part ( $\epsilon''$ ) represents dielectric losses due to dispersion, relaxation of free and bound water fractions.

$$\epsilon = \epsilon' - j\epsilon'' \quad [1]$$

Where;

$\epsilon$  = permittivity or dielectric permittivity.

$\epsilon'$  = Real part of permittivity

$\epsilon''$  = Imaginary part of permittivity.

## 2.2. Comparison with TDR

In contrast to frequency domain, the time domain systems measure and interpret electromagnetic signals as a function of time. A commonly used time domain system

(TDR) measures travel time of electromagnetic pulse in solid material. However reflection from the incident wave in TDR is affected by conductivity of the materials and therefore a correction is needed for materials with high salt content. Liu and Pinto, (1996) have stated that TDR method neglects the effects of material conductivity on reflection time as it relates attenuation only to permittivity. However it is both conductivity and permittivity which affect phase delay and attenuation. The wide band signals such as TDR (large frequency range) will experience pulse spreading due to different propagation speeds of different frequency components. This pulse spreading will cause errors in measurement of travel time. One way to correct this problem is to use the narrow band signals with determined frequency range or single frequency as it will allow isolation of conductivity effects from electrical permittivity through measurement of phase delays and magnitude of reflected pulse.

The frequency domain system (FDR) measures phase and magnitude of the electromagnetic pulse in materials rather than its travel time. This difference is very important when it comes to materials which are lossy i.e. conductive in nature. In such materials the time domain system performs very poorly due to signal attenuation and difficulties in retrieving wave forms. However, the frequency domain approach allows quantification of water content and salts simultaneously without extra effort such as i.e. probe coating or Fourier transforms etc. often required by TDR (i.e. Heimovaara 1995). Van Praagh et al., (2007) have reported an error of 10% in TDR measurement of moisture in solid wastes due to probe coating and increased reflection when rods have high impedance than coaxial cable.

### **3. EXPERIMENTAL STUDY**

#### **3.1 Apparatus**

##### *3.1.1 Dielectric probe and Network Analyser*

The measurement setup consisted of a network analyser (ENA-5061A, Agilent Technologies USA) which measures phase and magnitude of reflected signal from a reference electrical signal. A dielectric probe (Agilent, 85070E) connected to network analyser with an open ended coaxial cable of 50 ohm resistance was used to measure the reflection from ash samples. This probe has a frequency range of 300 MHz to 20 GHz. The measurement setup up was connected to a computer through General Purpose Interface Bus (GPIB) and operated with the help of Agilent dielectric software. The dielectric software provides data of both real and imaginary parts of the dielectric permittivity.

##### *3.1.2 Calibration of dielectric probe*

For system errors, i.e. instrumental drift, the calibration was done with air, shorting block and distilled water at room temperature. This one step calibration procedure was repeated before every measurement. The calibration can be stored with help of an electronic calibration (ECAL) block and can be refreshed every few minutes. In addition, the permittivity of known standards such as distilled water (80) and Teflon (2.0) was measured at regular intervals during the experimental runs. Figure 1 shows the dielectric probe configuration used in the study.

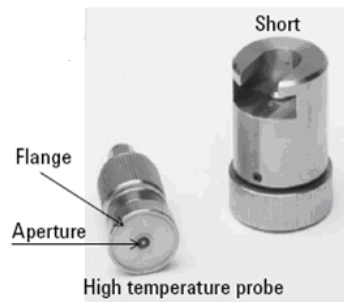


Figure 1: Dielectric probe and shorting block (source: Agilent Technologies, 2006)

### 3.1.3 Sampling depth

The effective sampling depth for the samples was determined by a method provided by the manufacturer. The depth of sampling depends on the permittivity, particle size, and heterogeneity of the MUT. For reflection measurement the sample size has to be larger than the wavelength in order to have only one contact boundary. In order to avoid fluctuations in measurements, the sample thickness was determined by  $20/\sqrt{\epsilon_r}$  (mm). Where  $\epsilon_r$  is relative permittivity of the material under test.

## 3.2 Experimental procedure

Two types of materials: bottom ash and stabilised industrial sludge were used for testing of moisture content with FDR. A sample of fine sand was also included as reference. The bottom ash was collected from an incinerator run by a regional waste management company (SYSAV) in the city of Malmö in southern Sweden. The BA samples were collected on July 3<sup>rd</sup> 2007 from an open pile which was filled between September 2006 and April 2007. Two 15 liter containers were used for sampling from the outer layer of the pile. The particle size ranged between 0 - 40 mm but for tests the samples were sieved and the ash fraction below 1mm was obtained. This fraction is most relevant for the bottom ash as it provides most of the water holding capacity and contains most of the pollutants. In order to test the impact of texture the BA samples were grounded to create a clay like material with particle size below 0.125 mm. At the time of our tests, however, the samples had been stored in laboratory since collection date. Therefore in terms of quality the bottom ash was highly weathered and in a relatively stable state.

Table 2 gives the type and physical properties of the samples used in this study. All samples were oven dried at 105 C° prior to measurements and four predetermined volumetric water contents; 0.1 to 0.4 m<sup>3</sup> m<sup>-3</sup> were used. The distilled water was used for preparing water contents and samples later were packed to correct bulk density in measuring container. Effect of salinity was tested with addition of saline solution at 10 dS/m at similar volumetric water content (VWC) as in case of distilled water. The measurements were performed over a range of 0.3 to 1.5 GHz with linear sweep which resulted in 51 data points. In each sample measurement were done at four points and at each point the measurement was replicated four times in order to average permittivity across the entire sample volume.

Table 2. Physical description of waste samples used in the study

	Type	Size (mm)	B.Density(gm/cm <sup>3</sup> )
1	Bottom Ash	< 1	1.92
2	Bottom Ash	0.125	2.6
3	Industrial Sludge	NA	0.98

#### 4. RESULTS AND DISCUSSION

Figure 2 shows the water content measurement with FDR in bottom ash sample at six selected frequencies. The real part of permittivity which represents here the energy storage is related to water content. It increases linearly with increasing volumetric water content (VWC). At VWCs between 0-0.10 m<sup>3</sup> m<sup>-3</sup> the difference in permittivity between different frequencies is very small. At low water content the water molecules are tightly absorbed to grains. Therefore differences among frequencies are not visible as most of the water is bound. However as the water content is increased the differences among frequencies start to appear. At high water content low frequencies are giving higher dielectric while higher frequencies are giving low permittivity. The permittivity is a frequency dependent variable and decreases with increasing frequency (Martinez and Byrnes, 2001). This is normal as at the dry end of the curve most of pulse energy is reflect back and differences due to wavelengths are small. However at the saturated end of the curve energy storage is greater and low frequency due to longer wavelengths achieve more penetration and thus the higher permittivity. Over all the permittivity varied between 2 to 14.5 over volumetric water content range of 0-0.4 m<sup>3</sup> m<sup>-3</sup>. These results are close to what Alex and Behari, (1996) obtained over a similar frequency and water content ranges in soils.

A somewhat similar pattern can be observed in figure 3 which shows the imaginary part of permittivity against volumetric water content. The dry end of the curves show very low loss which could be due to greater portion of bound water at low moisture. However after a transition zone (between 0.1 and 0.2 m<sup>3</sup> m<sup>-3</sup>) the portion of free water increases which results in larger imaginary part. The behaviour of imaginary part is qualitatively different as it is affected by electrolyte concentration which can be seen at higher water contents. The salt dissolution in sample increases with increasing moisture content and therefore the losses of electrical energy increase as well. The dielectric loss factor shows a clear dependence on moisture content. This demonstrates that FDR can be used to measure moisture content in lossy materials.



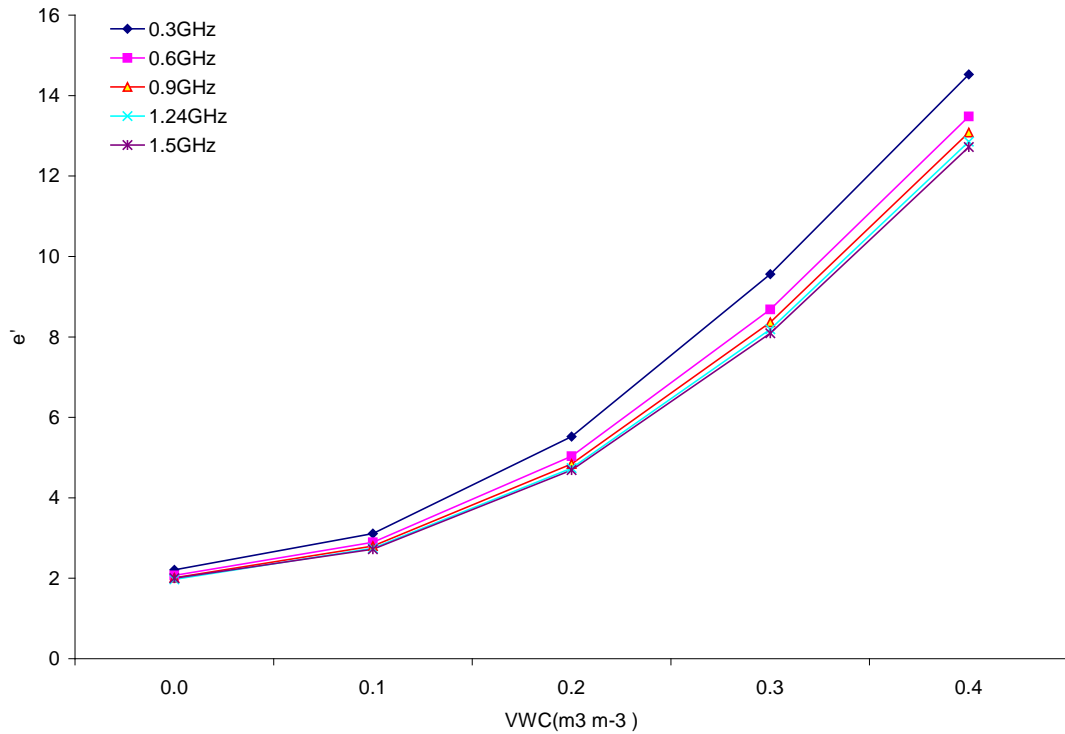


Figure 2: Real part of permittivity of BA versus volumetric water content

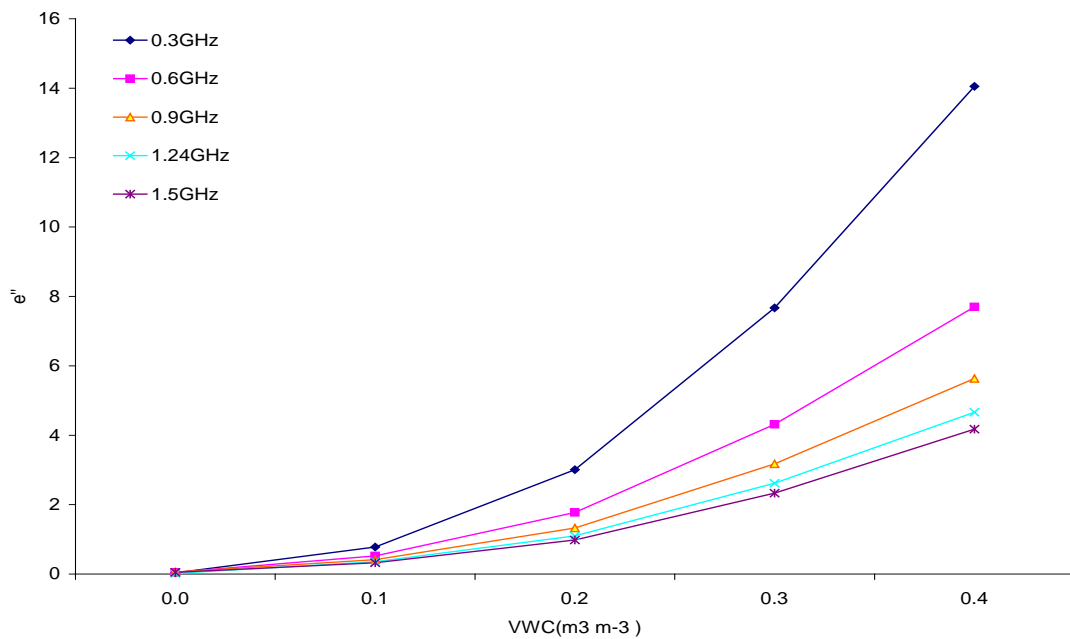


Figure 3: Imaginary part of permittivity of BA versus volumetric water content

#### 4.1. Impact of density and texture on permittivity

Figure 4 shows the permittivity of fine textured (<0.125 mm) bottom ash. The permittivity doesn't increase in a linear fashion and at water content of 0.30 m<sup>3</sup> m<sup>-3</sup> it actually tapers off. This is due to swelling behavior exhibited by bottom ash. As the surface area of fine grained sample is higher therefore absorption water molecule is

stronger as compared to coarse textured sample. Therefore at higher water content the permittivity is low. However differences among frequencies are similar as coarse textured sample. Figure 5 shows the imaginary part of a fine textured sample. The energy loss in fine textured sample is greater which is perhaps due to the release of salts as result of crushing. In fine textured sample the grains could also provide a continuous path for electrical current, therefore losses can substantially increase.

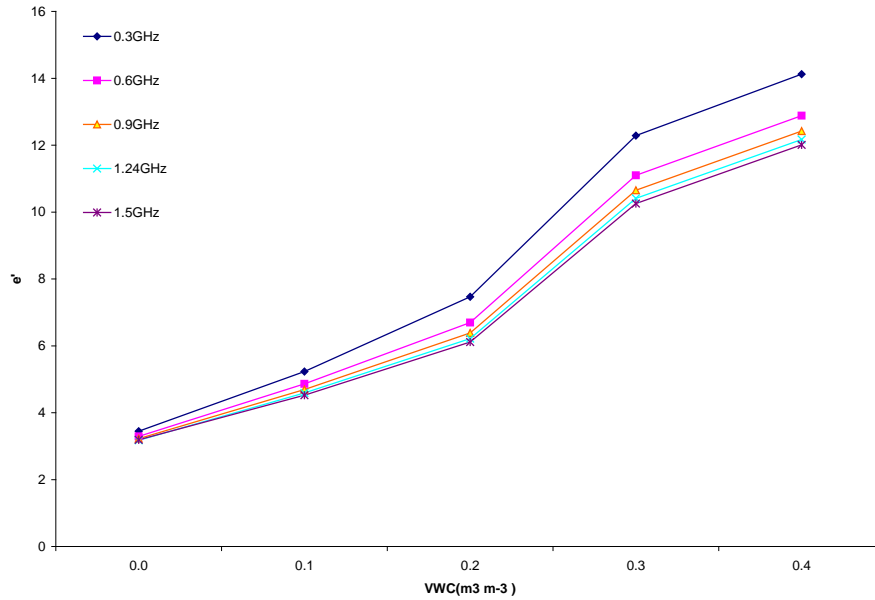


Figure 4: Impact of texture on measurement of permittivity of bottom ash

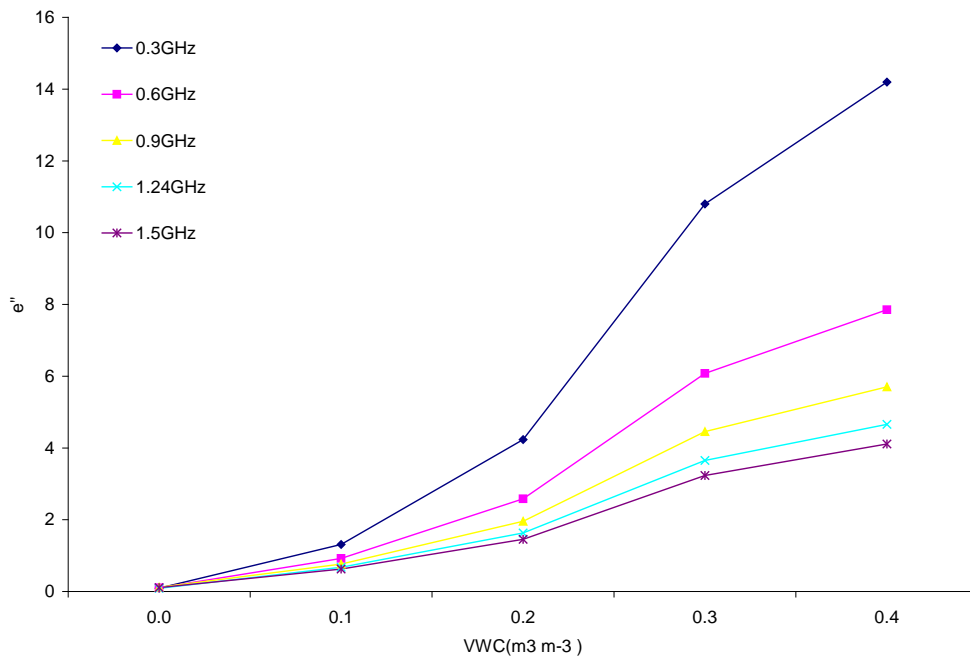


Figure 5: Imaginary part of permittivity of fine texture bottom ash at six different frequencies.

## 4.2. Impact of salinity on permittivity

The presences of solutes affect the permittivity measurement due to rise in bulk solution conductivity. Furthermore, the permittivity of water is 80 and relaxation occurs around 10 GHz. The permittivity of water is very sensitive to impurities which hinder the water molecule orientation along the electric field and lower the relaxation frequency. Figure 6 shows the comparison between samples mixed with distilled water (DW) and saline water with 10 dS/m conductivity at both low and high frequencies. However here DW water doesn't mean low salinity in pore water as bottom ash itself contains high amount of salts therefore background salinity of the samples was measure 1618  $\mu\text{S}/\text{cm}$ .

From figure 6 it is obvious that there are significant differences among the curves at similarly frequencies due to salinity levels. The real part of permittivity is increasing with both high water content and increasing frequencies. This is an interesting yet counterintuitive result as the real part of permittivity generally decreases with high salinities. One possible explanation to this is the fact that real part of permittivity is composed of polarisation and conductive losses as given by equation 2.

$$\epsilon'_{obs} = \epsilon'_{Pol} + 2\sigma / f \quad [2]$$

Where  $\epsilon'_{obs}$  is observed permittivity and  $\epsilon'_{Pol}$  is due to polarisation and  $2\sigma / f$  is term related to conductive losses.

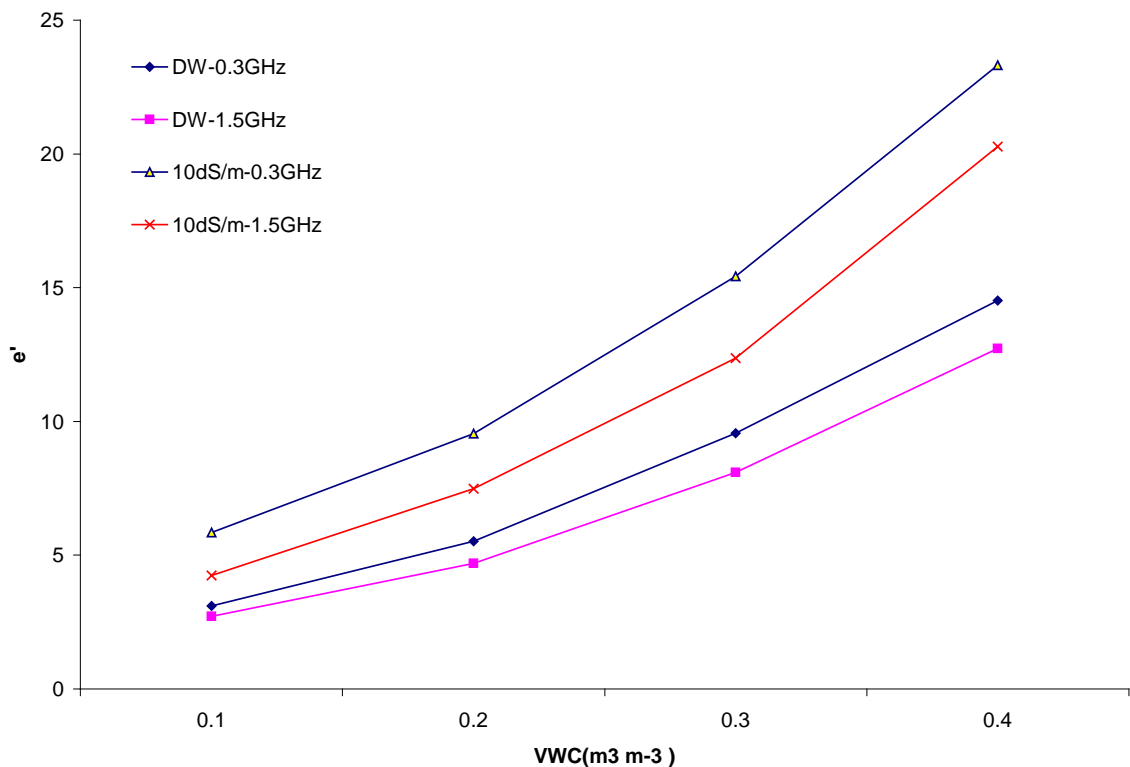


Figure 6: Real part of permittivity as affected by salinity at two different frequencies

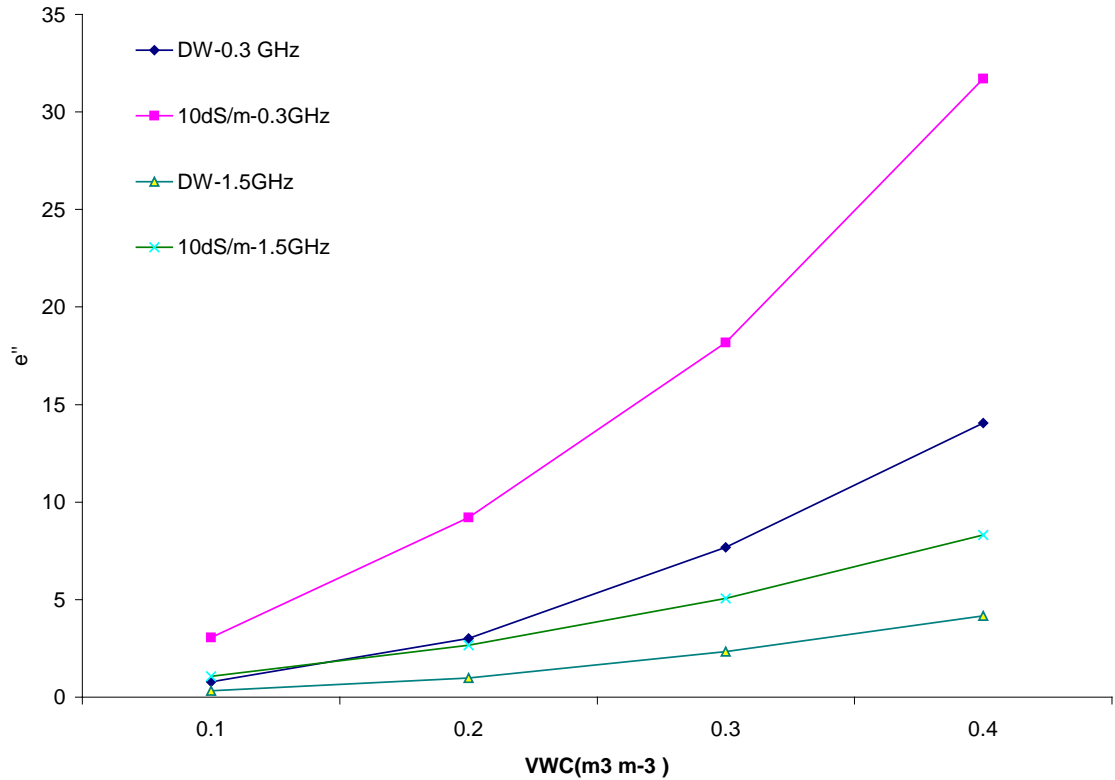


Figure 7: Impact of salinity on imaginary part of permittivity of BA as affected by salinity.

The second term in eq. 2 shows that conductive losses are inversely proportional to the frequency  $f$ . In frequency domain system which operates in microwave range the frequencies are higher than effective frequencies of most time domain system. Therefore the contribution of later term can be effectively ignored. Thus observed permittivity is solely resulting from polarisation. This is plausible as bottom ash is a very reactive substance and addition of saline solution can form additional molecules through ion association with dipole moment of their own. These molecules can increase the polarisation which is why the observed real part of permittivity is higher at high salinities. However this assumption will require further experimental work in order to be verified.

Nonetheless the result highlights the robustness of the method as permittivity is unaffected by salinity and only responding to variation in water content. This result is also in line with Lasne et al. (2008) who have reported that for small salinity values the real part varies as function of moisture content and remains largely unaffected by salinity. However imaginary part is affected strongly by both salinity and moisture. Figure 7 shows that for imaginary part at low frequency the impact of salinity is more pronounced. Wensink (1993) have reported that a low frequencies  $\epsilon''_0$  is very sensitive to changes in soil water conductivity above 10 mS/m. This results also point to robustness of the method as microwave frequencies the measurement of permittivity is unaffected by salts.

In order to highlight the impact of salinity on measurement the results were

compared with a sand sample mixed with water of 10 dS/m. The ratios of imaginary to real part of the permittivity of both sand and BA were calculated. Figure 8 provides a comparison of loss factors of BA at 0.3 GHz frequency. The sharp contrast between the two loss factors can be observed. For bottom ash the losses linearly increase with increasing water content. However in case of sand the increase is relatively low. This result highlights the differences in composition of the two materials for example bottom ash contains more mineral salts than sand. The increasing salt dissolution with increasing water content results in sharp rise in loss factor over entire water content range. However in case of sand the addition of salt water slightly increases the dielectric loss which is uniform over entire water content range.

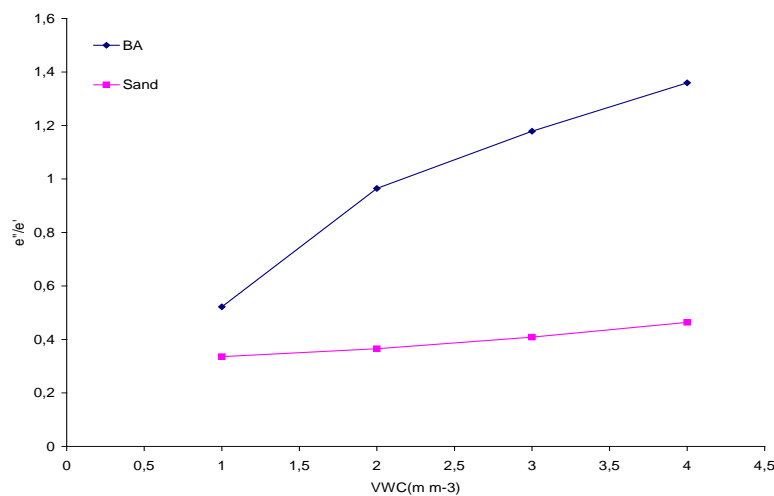


Figure 8: Comparison of loss factor ( $\epsilon''/\epsilon'$ ) of sand vs BA at 10 dS/m salinity and 0.3 GHz

### 4.3. Application of FDR on industrial sludge

The Figure 9 and 10 show the results which are similar to fine textured bottom ash as curve flatten around 30 % volumetric content. However there are very small differences in terms of frequencies. This could be due to highly fine texture and relative hydrophobic nature of the sludge as at higher water contents measurements were effectively in layer of water over solid sample. In fine textured materials the value of bulk density can change due to swelling behaviour. Also due to large surface area the ratio of bound water is greater than the free water. The results obtained from this sample reflect the similar but somewhat more pronounced impact of solid matrix at higher water contents as observed by Van Praagh et al. (2007)

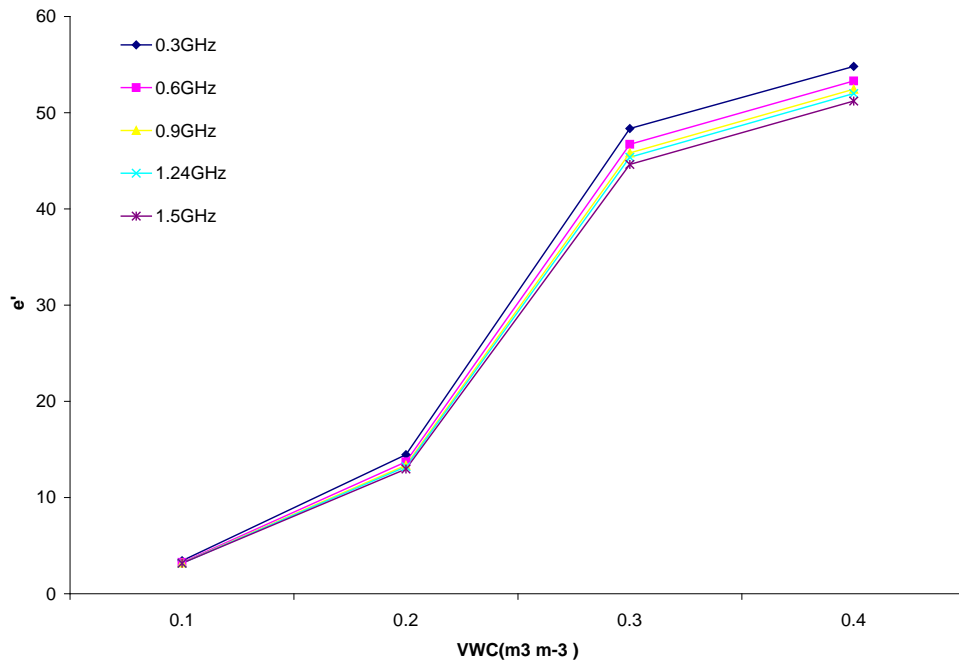


Figure 9: Real of part of permittivity of industrial sludge at six different frequencies.

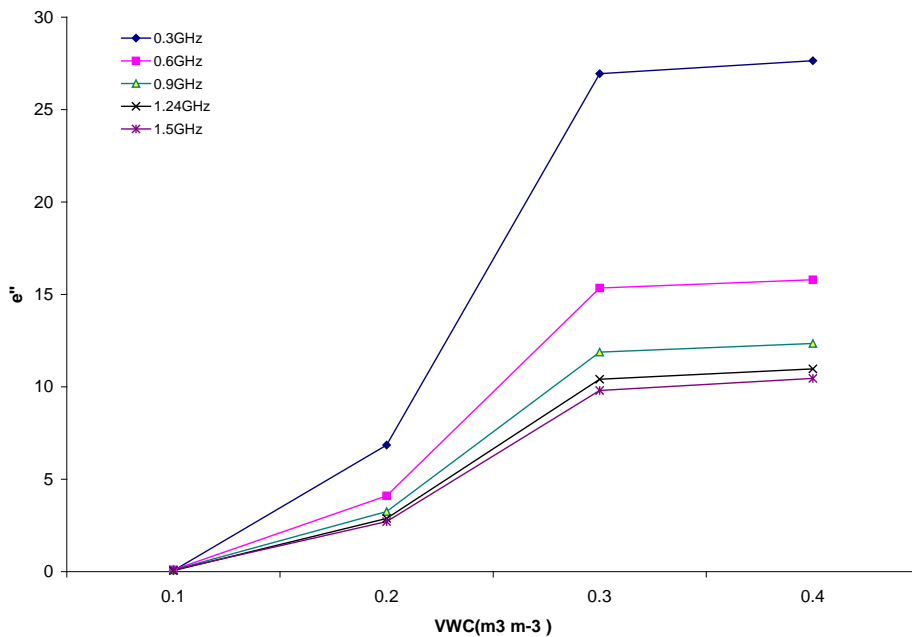


Figure 10: Imaginary part of permittivity of industrial sludge at six different frequencies.

#### 4.4. RELATION BETWEEN WATER CONTENT AND PERMITTIVITY

Heimovaara et al. (1994); Wensink (1993); Roth et al. (1990), and Hallikainen et al.(1985) have reported the measurements of frequency dependent dielectric soil behavior. The results from these measurements show that is difficult to describe the

relationship between textural characteristics and the frequency dependent complex dielectric properties of soils using one single model. The determination of water content and its relation to permittivity is complicated by the fact that most of the models available are developed for TDR whose effective frequencies are lower than the measurement range of FDR. Therefore a simple 3<sup>rd</sup> order polynomial was fitted (figure 11). Although it has different coefficients than described by Topp et al. (1980) but it provided a good fit.

$$\varepsilon' = -5 \cdot 10^{-05} \theta^3 + 0.0092 \theta^2 + 0.0202\theta + 2.1762 \quad [3]$$

The use of dielectric mixing models developed by Hallikainen et al., (1985 a&b) and polynomial by Topp et al.,(1980) failed to provide a good fit between measured and modelled permittivities. This was probably due to unknown or higher frequency ranges of such models. Curtis, (2001) have reported that the *Topp-model* functions well for frequencies around 100 MHz but at higher frequencies and moisture contents close to saturation (~0.4) this over-predicts the bulk relative permittivity by up to 20%. The models proposed by both Hallikainen et al. (1985 a&b) and Wang and Shmugge (1980) are valid for 1.4-18 GHz range which is well above the range our current set up. Their models are based on physical processes such as density, texture, salinity and temperature. However in material like bottom ash which is reactive substances the change in chemistry also has to be taken into account. Mixing of water with bottom ash results in reactions such as hydration, complexation and dissolution of minerals which can change chemistry and as well as physical properties of ash. Therefore interaction of ash with microwaves would be qualitatively different from soils. The impact of chemical change on measurement of permittivity would be the subject of further research.

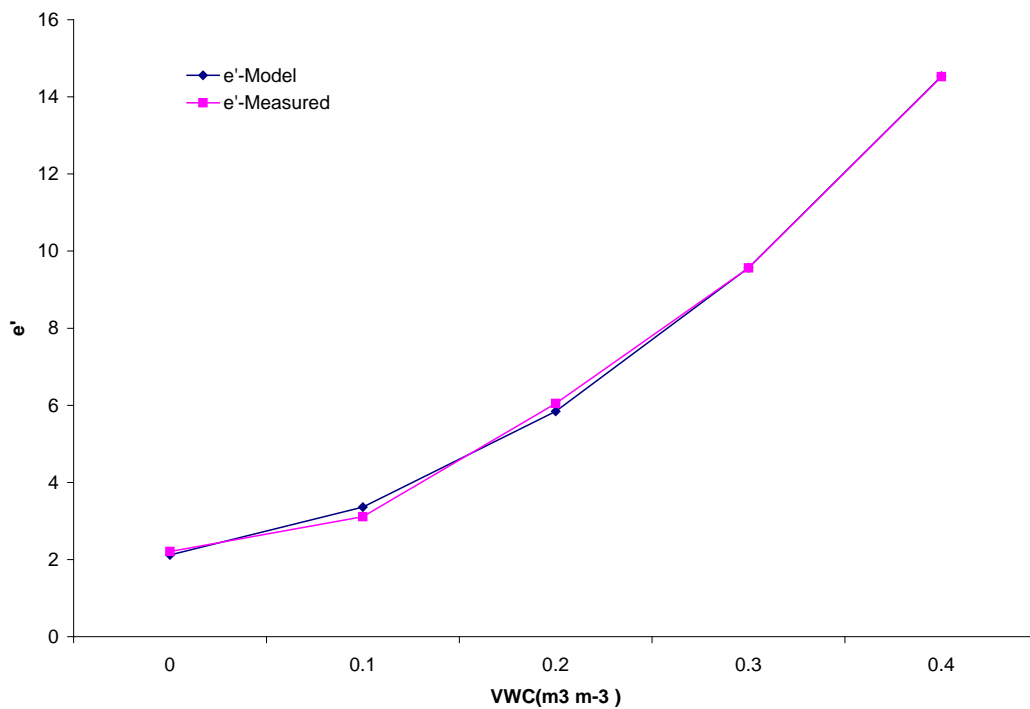


Figure 11. Relation between volumetric water content and permittivity at 0.3 GHz

## 5. CONCLUSIONS

The study has demonstrated the use of frequency domain approach for measurement of moisture content of waste material at laboratory scale. The results here indicate that despite lossy nature of waste materials this technique is capable of quantifying water content and electrical conductivity of the samples. The impact of salinity on permittivity has highlighted the importance of processes occurring at molecular level i.e. ion associations. This will require further analysis as bottom ash is highly reactive material and undergoes chemical transformation when mixed with water. Also the results highlight that in fine textured materials at higher VWC the changes in bulk density significantly affect the permittivity. Finally further work is needed on suitable dielectric model to relate water content to permittivity as most of the available empirical models failed to model this relation.

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support provided by Ångpanneföreningen and J. Gust. Richert foundation for this research work.

## REFERENCES

- Alex, Z.C. and Behari J., 1996. Complex dielectric permittivity of soil as function of frequency moisture and texture. *Indian Journal of Pure and Applied Physics*.34:319-323.
- Behari J., 2005. *Microwave dielectric behavior of wet soils*. Springer, New Dehli, India.
- Curtis, J.O., 2001. Moisture effects on the dielectric properties of soils. *IEEE transactions on geoscience and remote sensing*. **39**(1):125-128.
- Heimovaara, T.J., Bouten W., and Verstraten J.M., 1994. Frequency domain analysis of time domain reflectometry waveforms 2. A four-component complex dielectric mixing model for soils. *Water Resources Research*. **30**(2):201-209.
- Hallikainen, M. T., Ulaby F. T., Dobson M. C., Rayes M. A., and Wu L.K., (1985a). Microwave dielectric behavior of wet soil-part I. *IEEE Transactions on Geoscience and Remote Sensing*. GE23 (1): 25-34
- Hallikainen, M. T., Ulaby F. T., Dobson M. C., Rayes M. A., and L.K. Wu, (1985b). Microwave dielectric behavior of wet soil-part II. *IEEE Transactions on Geoscience and Remote Sensing*. GE23 (1): 35-46.
- Hyks, J., Astrup T. and Christensen T. H., 2009. Leaching from mswi bottom ash: Evaluation of non-equilibrium in column percolation experiments. *Waste Management* 29(2): 522-529.
- Kent M., 2001. Microwave measurements of product variables. In *Instrumentation*



*and Sensors for Food Industry*. E.K. Rogers and CJB, Brimlow, Eds. CRC Press LLC. p 233-277.

- Lasne Y., Paillou P., and Freeman A., 2008. Effect of salinity on the dielectric properties of geological materials: Implications for soil moisture detection by means of radar remote sensing. *IEEE Transactions on Geoscience and Remote Sensing*. 46(6):1674-1687.
- Liu X., and Pinto N.G., 1996. Frequency domain–  $\pi$  phase-shift reflectometry for soil moisture measurements: 1.Theory. *Sensors and Actuators. A* 55:127-132.
- Martinez, A. and Byrnes A.P., 2001. Modeling dielectric-constant values of geologic materials: an aid to groundpenetrating radar data collection and interpretation. *Current Research in Earth Sciences, Bulletin 247, part 1*.  
<http://www.kgs.ukans.edu/Current/2001/martinez/martinez1.html>. Accessed on 4th April 2009.
- Ore S., Todorovic J., Ecke H., Grennberg K., and Lidelöw S., 2007. Toxicity of leachate from bottom ash in a road construction. *Waste Management*. 27: 1626–1637.
- Powers, M.H. (1997). Modeling frequency-dependent GPR. *The Leading Edge*. 16(11):1657-1662.
- Ribbing, C., 2007. Environmentally friendly use of non-coal ashes in Sweden. *Waste Management*. 27:1428–1435.
- Robinson D.A., Schaap M., Or D., and Jones S.B., 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone Journal*. 2:444-475.
- Roth, K., Schulin R., Flühler H., and Attinger W., 1990. Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. *Water Resources Research*. 26(10):2267-2273.
- Topp G.C., Davis J.L., and Annan A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*. 16:574–582.
- Trabelsi S., and Nelson S.O., 1998. Density independent functions for on-line microwave moisture meter: a general discussion. *Measurement Science and Technology*. 9:570-578.
- Van Praagh M., Persson M., and Persson K.M., 2007. Assessment of hydrological parameters in pre-treated waste by time domain reflectometry. *Sardinia 11<sup>TH</sup> Symposium 2007 CISA Publisher, Cagliari, Italy*. 1-5 October 2007.
- Wensink, W.A., (1993) Dielectric properties of wet soils in the frequency range 1-3000 MHz. *Geophysical Prospecting*. 41: p. 671-696.

# **Microwave Dielectric Sensing of Moisture in Municipal Solid Waste Incinerator Bottom Ash (MSWI-BA).**

Aamir Ilyas\*, aamir.ilyas@tvrl.lth.se, Water Resources Engineering, Lund University, Sweden.

Magnus Persson, magnus.persson@tvrl.lth.se, Water Resources Engineering, Lund University, Sweden.

Martijn van Praagh, Martijn.van\_Praagh@mv.lu.se, Environmental Sciences, Lund University, Sweden.

## **Introduction**

The detection of moisture in waste materials presents a special challenge due to heterogeneity of the medium and high amounts of electrolytes. Under the new EU regime of dry landfills the control of moisture would be a critical factor in achieving the objective of zero leachate emissions. Rapid and non-destructive measurement techniques would be helpful in real time monitoring of infiltration fronts through the landfills. The commonly available techniques (e.g. TDR, Time Domain Reflectometry) are not suitable due to high conductivity of waste materials. Even at moderate salinity levels i.e.  $2\text{dSm}^{-1}$  the attenuation of TDR signal drastically lowers its ability to determine the water content (Jones and Or, 2004). One way is to transform the signals through Fourier transforms into frequency domain (i.e. Heimovara, 1994; Jones and Or, 2004). However this militates against the logic of rapid detection as these calculations increase the analysis time. The other alternative is to use dielectric measurements in frequency domain. This method, unlike most commercial sensors, uses microwave ( $> 300$  MHz) frequencies which are less susceptible to salts. Therefore, present study tested the frequency domain reflectometry (FDR) to estimate the moisture content of bottom ash. The objective was to test the suitability of this method and compare its performance with the TDR.

## **Materials and Methods**

Bottom ash (BA) obtained from a local municipal solid waste incineration plant was used for testing of moisture with FDR. The samples of BA at the time of measurement were 1.7 years old. The ash particle fraction below 1mm was used because it provides most of the water holding capacity. The samples were oven dried at  $105\text{ C}^{\circ}$  for 24 hours prior to measurements. Deionised water was used to prepare water contents ranging from 0.1 to  $0.4\text{ m}^3/\text{m}^3$ . The measurement setup for frequency domain included a network analyzer, a dielectric probe and the dielectric software for data acquisition.

## **Results and Discussion**

The dielectric permittivity represents the energy storage in a sample which is related to water content (figure 1). Over all the permittivity varied between 2 to 42 over a volumetric water content range of  $0\text{-}0.4\text{ m}^3/\text{m}^3$ . The TDR gives similar estimates of permittivity at low water contents ( $< 0.15$ ) but at higher water contents it starts to overestimate the permittivity. This shows that at higher water contents due to 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 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 ratio of bound to bulk water content in soils. While 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. As at higher frequency the permittivity is lower because the penetration depth decreases. This is plausible as higher frequencies have shorter wave lengths which mean lower penetration depth.

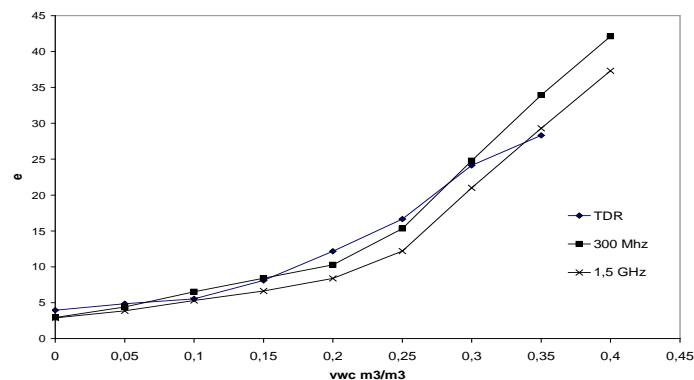


Figure 1. Dielectric constants as a function of volumetric water content ( $\text{m}^3 \text{m}^{-3}$ ) measured with FDR at two different frequencies and with TDR.

## Conclusions

The results demonstrate that the FDR measurements are less affected by salinity than TDR which reduces the effective frequency as salinity level increases. This results in over estimation of permittivity over similar water content. More information is needed on impact of salinity on both FDR and TDR measurements. Therefore future work with more waste materials and different salinity levels is planned.

## References

- Heimovaara, T. J. (1994). Frequency domain analysis of time domain reflectometry waveforms 1.Measurement of the complex dielectric permittivity of soils. *Water Resources Research* 30(2): 189-199.
- Jones, S. B. and D. Or (2004). Frequency domain analysis for extending time domain reflectometry water content measurement in highly saline soils. *Soil Science Society of American Journal*. 68: 1568-1577.
- Robinson D.A., M.G. Schaap, D. Or and S.B. Jones, 2007. On the effective measurement frequency of time domain reflectometry in dispersive and non conductive materials. *Water Resources Research*.41:1-9.

Wraith, J. M. and D. Or, (1999). Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development. *Water Resources Research*.35 (2):361–369