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MEASUREMENT OF MOISTURE IN MORTAR USING A COPLANAR WAVEGUIDE

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Abstract – Increasingly more non-destructive testing methods are being developed in a civil engineering context, but many of them cannot be applied when only one surface of the structure can be accessed. In order to measure moisture level in such concrete structures as dams or tunnels, a coplanar line was designed, capable to measure the permittivity evolution as well as the loss factor. Measurements on salinity of water and setting of mortar were performed, showing a dependence on physical magnitudes of interest with the electrical parameters measured.

Keywords: coplanar waveguide, mortar non-destructive testing, permittivity

1. INTRODUCTION

The increasing demand for non-destructive testing methods applied to civil engineering led in the recent years some researchers to develop different methods to deduce physical parameters from the evaluation of the measurement of an electrical magnitude. Previous works have reported the difficulties of measuring big samples by low frequency impedance measurements [1], so there is a need to use higher frequencies to determine the electrical parameters of interest. The permittivity and propagation losses are considered the most significant indicators of the moisture level.

Many methods to determine the permittivity of non-homogeneous materials have been carried out. Huebner and Kufper [2] developed a three-wire planar sensor used to measure the permittivity of soils by Time Domain Reflectometry (TDR) techniques. Similarly, others have applied the same principle to measure concrete permittivity [3] by a two-port sensor, becoming a Time Domain Transmission (TDT) technique, analogous to TDR.

However, none of these techniques are of direct application to an in-situ concrete situation, as the concrete needs to be surrounded or filled with the material under characterisation. Moreover, sometimes only one of the sides of the concrete is accessible, e.g. in dams, tunnels, big walls and so on. Particularly in the case of dams, it is crucial to know the moisture level of the walls from the outer face in order to estimate possible damages caused by leaking. Our aim is to determine the moisture level of a mortar wall by measuring its permittivity and loss factor using a planar line as a sensor.

In this work, a coplanar waveguide with 2 ports was developed to be attached to one of the faces of the concrete and a TDT technique was used. As a result, the analysis of the s_{21} parameter provided with useful information about the moisture level on the different samples tested. Prior to measuring directly mortar samples, measurements on water were performed to verify the suitability of the setup.

2. THEORETICAL BACKGROUND

The propagation of waves along lines depends on its effective permittivity, which is function of the geometry of the line and the permittivity (or dielectric constant) of the medium. As the permittivity of the medium varies with factors such as temperature or moisture content, these properties could be studied studying the propagation of waves along an appropriate line. Many coplanar sensors have been studied before [4], which can be placed in contact with the sample under test in order to provide useful information about its physical properties.

The propagation of waves in a non-magnetic lossy medium is defined by a propagation constant expressed as

$$\gamma = j\frac{2\pi}{\lambda}\sqrt{\varepsilon' - j\varepsilon''} = \alpha + j\beta \qquad (1)$$

where λ is the free space wavelength, ε' is the dielectric constant of the medium and ε" represents the imaginary component of this permittivity, associated with the loss factor of the medium. The travelling wave for TEM modes in a waveguide has a propagation factor of the form

$$e^{-\gamma z} = e^{-\alpha z} e^{-j\beta z}, \qquad (2)$$

in which z is the longitudinal distance, α is the attenuation constant of the waveguide and β is the phase constant. From (1) and (2) it can be inferred that for a low-loss medium the dielectric constant can be obtained from the phase of the propagated wave (φ) as follows:

$$\left|\frac{\Delta\varphi}{\Delta f}\right| \approx \frac{2\pi z}{c}\sqrt{\varepsilon'}, \qquad (3)$$

where f is frequency of the propagated wave, and c represents the speed of light in free space.

Consequently, if the permittivity is constant for a certain range of frequencies, it can be estimated by measuring the phase slope of the transmitted wave. The loss factor will provide information about the attenuation constant.

However, when using a Coplanar Waveguide (CPW) an effective dielectric constant is defined, since the measured permittivity is not directly the medium permittivity but a combination of the dielectric constant of the substrate, the surrounding air and the material under test. The CPW initially proposed by C.P. Wen [5] consisted on three conductors on the surface of a substrate. The characteristic impedance can be calculated as

$$Z_0 = \frac{30\pi}{\sqrt{\varepsilon_{eff}}}\cdot\frac{K(k)}{K(k')}\,\Omega \tag{4}$$

where K(x) is the complete elliptic integral of the first kind, and

$$k = \sqrt{1-k'} = \frac{a}{b} \tag{5}$$

where a and b are geometrical dimensions of the CPW as it is showed in figure 1.

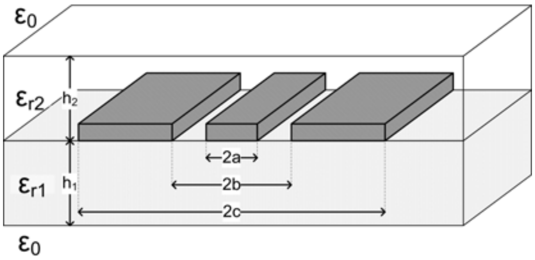

Fig. 1. Two-layer Coplanar Waveguide

In this work a two-layer CPW was designed, so the effective permittivity was calculated using formulae developed for multilayered CPW with finite ground planes [6]:

$$\varepsilon_{eff} = 1 + \sum_{i=1}^{2}\frac{1}{2}\left(\varepsilon_{ri} - 1\right)\frac{K(k)}{K(k')}\frac{K(k'_i)}{K(k_i)} \tag{6}$$

where

$$k_i = \frac{\sinh\left(\frac{\pi c}{2h_i}\right)}{\sinh\left(\frac{\pi b}{2h_i}\right)}\sqrt{\frac{\sinh^2\left(\frac{\pi b}{2h_i}\right) - \sinh^2\left(\frac{\pi a}{2h_i}\right)}{\sinh^2\left(\frac{\pi c}{2h_i}\right) - \sinh^2\left(\frac{\pi a}{2h_i}\right)}} \tag{7}$$

where c, h_1 and h_2 are geometrical dimensions of the CPW as it is showed in figure 1.

Therefore, as the dielectric constant of the substrate and air are perfectly known, from the measurement of the effective permittivity of the whole setup, the real permittivity can be numerically estimated.

3. MATERIALS AND METHODS

3.1. Sensor design

The main requirement of the sensor is that it has to be capable of measuring the magnitude of interest from only one accessible side of the sample under test. Thus, since a planar line is suitable for this purpose, a Coplanar Waveguide (CPW) was chosen, for it has low losses and can be easily adapted to 50 Ω in the input ports. The dimensions of the waveguide are 600×150×1,6 mm, in accordance with the dimensions of many standard concrete samples for flexural tests [7].

The CPW, fabricated on a FR4 substrate, has a central conductor of 3 mm and a maximum gap of 62,5 mm in its broader end, which leads to an impedance of 200 Ω, so an 1:4 impedance transformer was designed in order to minimise the wave reflection coefficient, which theoretically can be always under 0,21, accomplished by an exponential taper, a smooth transition between both ends. The length of the taper (30 cm) is directly related with the low-frequency limit [8], in this case fixed at 300 MHz, and the dimensions of the taper were designed for an ideal bulk with a permittivity of 4, which is near the expected values from concrete or mortar.

3.2. Measurement setup

Wideband measurements were performed using a HP8753C Vector Network Analyser (VNA), in the range of 300 MHz to 3 GHz. Data was acquired by a PC via GPIB connection, using a LabView automation driver. 801 points per sample were measured, leading to a resolution of 3,37 MHz, with an input power of 0 dBm. The measurements were then calibrated using a TRL algorithm, more suitable for planar structures than the traditional SOLT [6].

3.3. Preparation of samples

All the tests were performed on a 600×150×150 mm methacrylate box placed over two wooden stands, to avoid interferences due to metallic objects. Water measurements were performed using tap water. Mortar prismatic samples (600×150×30 mm) were produced using Ordinary Portland Cement and calcareous sand, passed through a 5 mm sieve, with a sand/cement ratio of 3,0 and a water/cement ratio of 0,50. No additives were used. The mortar was covered with a plastic during the first 24 hours, then uncovered and air-dried.

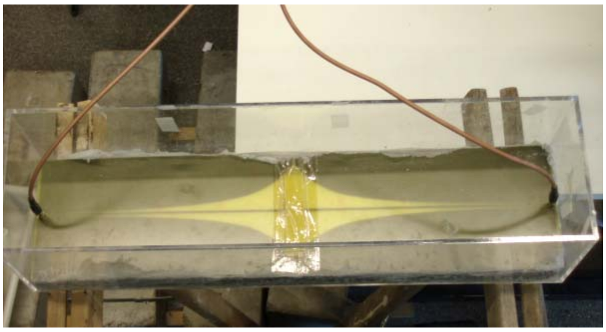

Fig. 2. Experimental setup.

4. RESULTS AND DISCUSSION

4.1. Salinity measurement

As a preliminary result, the sensor was placed on a methacrylate box, at 5 cm from the bottom and this gap was filled with water. Then, common salt was added progressively in order to measure the influence of water salinity to the permittivity measurement. The propagation in a CPW line is quasi-TEM so its field lines are mainly parallel to the propagation direction [10]. According to theoretical works [11], the penetration depth inside the material should be around a 60% of the maximum gap between the lines, which means that the sensor has a maximum penetration of 37,5 mm. Effective permittivity is shown in figure 3, as an indirect measurement of permittivity, showing that an increase in the salinity is directly related with an increase in the effective permittivity measured by the sensor.

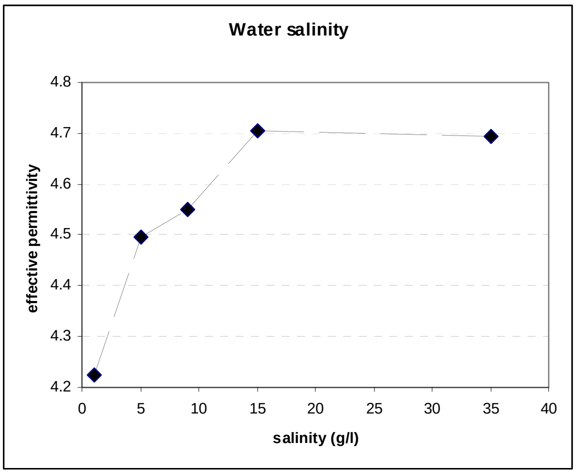

Fig. 3. Dependence between effective permittivity and salinity of water.

The effective permittivity should be considered as a magnitude directly related with the physical permittivity of the material under test. Since the relation between the material permittivity and the measured effective permittivity depends on the line geometry, a direct relation between them has to be established (figure 5).

4.2. Mortar drying

The planar line was placed over the mortar just after casting it. The bulk was then measured for 24 hours sampling every 5 minutes. The s_{21} parameter was analysed in order to obtain the effective permittivity of the setup as well as its propagation losses (figure 4). As it was expected in general, the permittivity tends to diminishes as the mortar sets, since as the reaction takes place, there is less presence of water, both because of drying and setting. As the permittivity of water is around 80 and the expected permittivity of mortar is in the range of 3 to 8, according to other authors [12], a decreasing tendency is expected as the amount of water decreases. However, two singular effects can be observed. Firstly, in the early minutes, there is a rapid decrease of the permittivity, which is due to the excess of water, which in fact progressively leaked from the mould and ends after the initial setting time. Secondly, an increase in the permittivity is observed during the subsequent 6 hours, until the end of the final setting time, while the temperature is significantly decreasing. After then, the effective permittivity starts to decrease as there is less hydrating water in the sample. Finally, the effective permittivity starts to stabilise around 2,15 and showed less significant variations for some days.

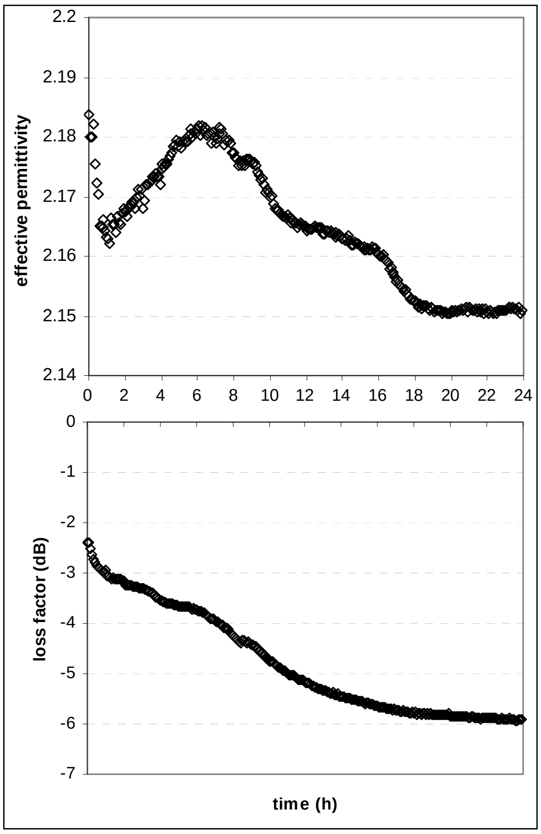

Fig. 4. Evolution of the mortar sample during the first setting day (a) effective permittivity and (b) loss factor measured at 500 MHz.

As for the loss factor, it shows a constant decrease, since the less water in the sample, the less attenuation, for water has a higher conductivity than dried mortar, so higher losses are expected in the early hours, and a gradual decrease until a final stable value is reached.

The relative variations of permittivity show the amount of water in the mixture. However, the measured values are highly affected by the gap between the sample and the sensor. If a direct relation between the material permittivity and measured permittivity is needed, the gap influence should be considered. Figure 5 shows the relation between both magnitudes for the geometry of the sensor used, calculated from the multilayer dielectric model presented before. In this work, gaps between 5 and 8 mm are assumed, since the sample was covered with plastic, which leads to a permittivity from 4,5 to 7. For further works it will be necessary to fix this gap in order to estimate the sample permittivity precisely.

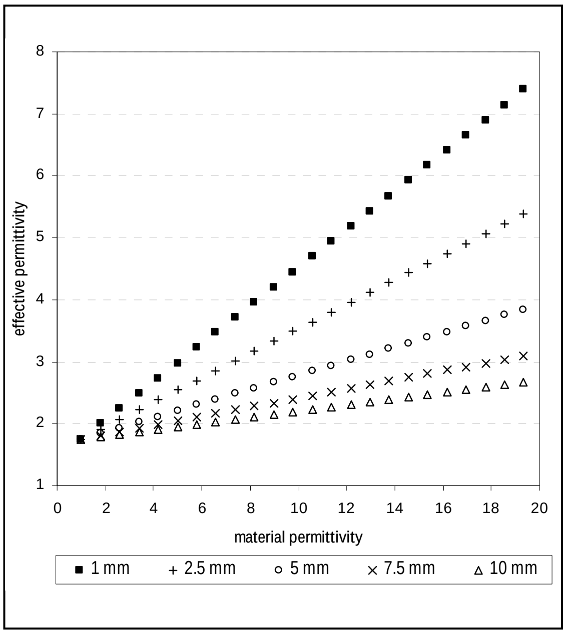

Fig. 5. Air gap influence on the relation between measured permittivity and material permittivity.

5. CONCLUSIONS

A planar sensor, based on a CPW line, was designed, suitable to measure the permittivity and losses of a mortar sample in situations in which only one face of the structure can be accessed, such as tunnels and dams. Wideband measurements from 300 MHz to 3 GHz were performed in order to estimate the moisture level of a mortar sample. Previously, effective permittivity dependence on salinity of water had been measured, showing a relation between the salt concentration and effective permittivity. Finally measurements on a mortar sample showed a decrease in the loss factor as the mortar sets at early stages while effective permittivity showed a turning point after the initial setting time and after the final setting time, probably related to temperature changes in the sample. The influence of the gap between the sensor and the sample was also studied. Further work is necessary in order to apply these measurements to in-situ structures as well as to obtain the best estimation of permittivity from effective permittivity models.

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REFERENCES

[1] J.M. Torrents, P. Juan-Garcia, and A. Aguado, “Electrical impedance spectroscopy as a technique for the surveillance of civil engineering structures: considerations on the galvanic insulation of samples”. *Measurement Science & Technology*, 2007. 18(7): p. 1958-1962.

[2] C. Huebner and K. Kupfer, “Modelling of electromagnetic wave propagation along transmission lines in inhomogeneous media”. *Measurement Science & Technology*, 2007. 18(4): p. 1147-1154.

[3] S. G. Millard, M.R. Shaw, S.M. Riad, A. Sharri and J.H. Bungey, “Coaxial transmission lines: Development of test procedures for concrete”. *Journal of Materials in Civil Engineering*, 2001. 13(3): p. 202-208.

[4] S.S. Stuchly and C.E. Bassey, “Microwave coplanar sensors for dielectric measurements”. *Measurement Science & Technology*, 1998. 9(8): p. 1324-1239.

[5] C.P. Wen, “Coplanar Waveguide: a Surface Strip Transmission Line Suitable for Nonreciprocal Gyromagnetic Device Applications”. *IEEE Transactions on Microwave Theory and Techniques*, 1969. MT17(12): p. 1087-1090.

[6] R.N. Simons, *Coplanar waveguide circuits, components and systems*. New York [etc.]: Wiley-Interscience, 2001

[7] NBN-B-15-238, “Tests on Fibre Reinforced Concrete - Bending Test on Prismatic Samples”, in *Norme Belge*. Institut Belge de Normalisation: Brussels, Belgium, 1992

[8] D.M. Pozar, *Microwave engineering*, 3rd ed. New York [etc.] John Wiley & Sons, 2005

[9] Engen, G.F. and C.A. Hoer, “Thru-Reflect-Line: An Improved Technique for Calibrating the Dual Six-Port Automatic Network Analyzer”. *IEEE Transactions on Microwave Theory and Techniques*, 1979. 27(12): p. 987-993.

[10] K.C. Gupta, R. Garg, I. Bahl and P. Bhartia. *Microstrip lines and slotlines*. 2nd ed. Artech House microwave library. Boston, London: Artech House, 1996.

[11] A.D. Seagar, D.C. Barber, and B.H. Brown, “Theoretical limits to sensitivity and resolution in impedance imaging”. *Clinical Physics and Physiological Measurement*, 1987. 8 (suppl A): p. 13-31.

[12] S. Peer, J.T. Case, E. Gallaher, K.E. Kurtis and R. Zoughi, “Microwave reflection and dielectric properties of mortar subjected to compression force and cyclically exposed to water and sodium chloride solution”. *IEEE Transactions on Instrumentation and Measurement,* 2003. 52(1): p. 111-118.