Measurement Notes

Note 65

10 January 2014

Measurement of Complex Permittivity of Large Concrete Samples with an Open-Ended Coaxial Line

Bertrand Daout, Marc Sallin

Montena Technology, route de Montena 89, Rossens, Switzerland

bertrand.daout@montena.com, marc.sallin@montena.com

Heinz Wipf

Skyguide, Wangen b. Dübendorf, Switzerland

heinz.wipf@skyguide.ch

Abstract

A 70 mm-open-ended coaxial line probe was developed to perform measurements of the dielectric properties of large concrete samples. The complex permittivity was measured in the frequency range 50 MHz – 1.5 GHz during the hardening process of the concrete. As expected, strong dependence of water content was observed.

Table of contents

1. Introduction

The dependence of the complex permittivity of concrete on its water content and/or ambient moisture is of great interest, especially when considering interactions of concrete buildings with electromagnetic waves.

For instance, ground penetrating radars operating at high frequencies from 300 MHz to 1.5 GHz are used to investigate surface soils and to locate small or large buried objects including rebar in concrete [1].

The monitoring of dielectric properties during the hydration in fresh concrete and its drying process have previously been performed by using a parallel plate capacitor technique at a single low frequency (20 MHz) in [2]. Measurements of complex permittivity of concrete up to 900 MHz are reported in [3] using an open-ended coaxial probe, and up to 1 GHz in [4] using a closed coaxial reflection/transmission cell with machined samples.

In this paper, a probe using the principle of an open-ended shielded coaxial line is proposed, allowing a broadband measurement of the complex permittivity of the concrete during its solidification for a range of frequencies up to 1.5 GHz and also allowing in situ addition of water during the curing process. Due to the size of the current test set-up, no standard gravel (no pebble) was put in the mix which was only made with cement, sand, small gravel and water.

2. Concrete and water content

2.1 Hydration process

Water is a key reactant in the cement or concrete hardening process (hydration). Water and cement initially form a fluid that will aggregate particles of cement, sand and gravel. During the hydration, chemical changes occur slowly, eventually creating new crystalline products, heat evolution, and others. After 2 days, the hydration process is almost finished and the concrete is hard but the curing then continues some days. The exceeding water which is not chemically transformed into the concrete will evaporate or stay in it, depending on the external air moisture conditions.

A standard concrete is made of around 14% of cement, 7 % of water, 77 % of sand and gravel and some optional additives. Half of the water takes part in the chemical reaction and half remains as water.

2.2 Water content

The interest in interactions of electromagnetic waves with building structures typically occurs within industrial und urban areas. At the outset of the study it was chosen to investigate into the water content critically governing the constitutive parameters ε and σ of a typical building construction concrete wall in moderate middle European climate exposed to characteristic precipitation rates.

Computer simulations made by the Frauenhofer Institute in Germany show that after the hydration and curing processes have ceased the water content in a concrete wall, separating the inside from the outside is not uniformly distributed. The reasons are temperature and moisture differences on either side of the side of the wall.

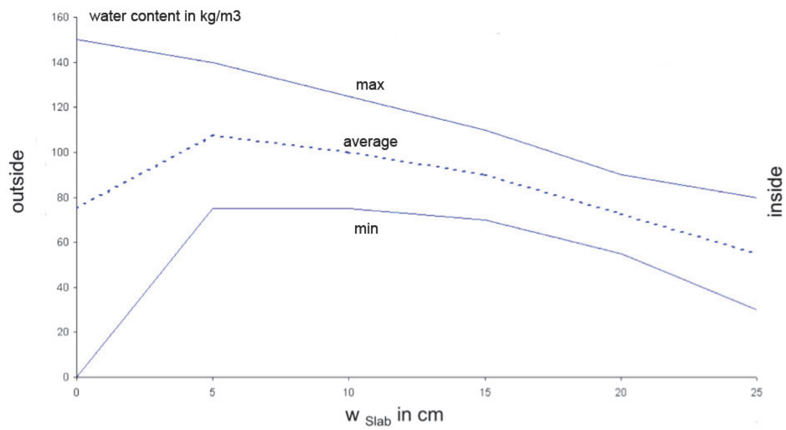

Fig. 1: Simulated water content over time in a concrete slab of width w = 0.25 m representing a typical concrete building wall.

The graph shows, that a building wall may be subdivided coarsely into three sections having different variability of water content. The variability in our example shows a decrease from the outside to the inside.

3. Theory

3.1 Coaxial line reflection method

In [5], several configurations of coaxial lines are proposed and compared. The chosen one is shown in Fig. 2. In this method, the sample constitutes a part of the coaxial line.

The relative complex permittivity of the sample material $\varepsilon^* = \varepsilon' - j\varepsilon''$ is calculated from the measured reflection when the sample is placed into a coaxial line terminated by a circular waveguide.

In this configuration, the sample thickness *d* has an influence on the uncertainty of the permittivity measurement. Its value should be optimized in function of the considered material. The optimal thickness is developed in [5] to be:

$$d = \frac{\lambda}{2\pi\sqrt{\varepsilon'^2 + \varepsilon''^2}} \qquad (1)$$

Since the water content changes as the concrete cures, it is expected that the complex permittivity and the uncertainty will change during the curing process. The thickness *d* was chosen to provide the best accuracy for a dry concrete at 1.5 GHz. Therefore its value is fixed to 10 mm.

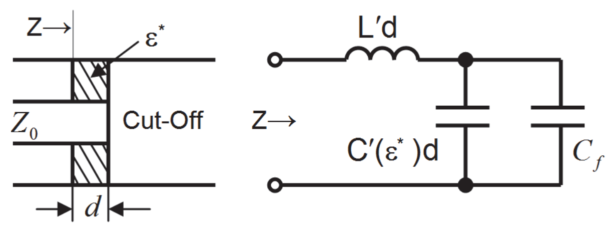

Fig. 2. Sample holder configuration and its equivalent circuit

C_f is the fringe capacitance at the interface of the coaxial line and the circular waveguide. Its value depends on the mechanical dimensions of the waveguide. For our experimental fixture, a calculated value of 0.9 pF is assumed for C_f [6].

The normalized input impedance *Z* at the interface between the nominal coaxial transmission Z_0 and the loaded coaxial transmission line before the circular waveguide is:

$$Z = j\omega L'd + \frac{1}{j\omega(C_f + C'(\varepsilon^*)d)} \tag{2}$$

Where $L' = Z_0 / c$ is the inductance per unit length of the coaxial line, $C'(\varepsilon^*) = 1/Z_0 c$ is the capacitance per unit length of the coaxial line, c is the velocity of light, Z_0 is the characteristic impedance of the coaxial transmission line, ω is the angular frequency. This capacitance $C'(\varepsilon^*)$ depends on the dielectric constant of the sample material.

The permittivity can then be expressed from the impedance:

$$\varepsilon^* = \frac{\lambda}{j2\pi d}\frac{1}{Z/Z_0 - j2\pi d/\lambda} - \frac{\lambda Z_0 \omega C_f}{2\pi d} \tag{3}$$

It is more convenient to express the permittivity as a function of the complex reflection coefficient $\Gamma^* = \Gamma e^{j\Theta}$

$$\varepsilon^* = \frac{\lambda}{2\pi d/\lambda}\left[\frac{1-\Gamma^*}{(2\pi l/\lambda)(1-\Gamma^*) + j(1+\Gamma^*)} - \frac{Z_0\omega C_f}{\lambda}\right] \tag{4}$$

Assuming that $(d/\lambda)^2 << 1$, *ε'* and *ε"*, respectively real and imaginary parts of complex permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$ are calculated from the reflection coefficient's amplitude Γ and phase Θ according to the formula [7]:

$$\varepsilon' = \frac{\lambda}{2\pi d}\left(\frac{(1+\Gamma^2 - 2\Gamma\cos(\Theta))\left(\frac{2\pi d}{\lambda}\right) - 2\Gamma\sin(\Theta)}{1+\Gamma^2 - 4\Gamma\sin(\Theta)\left(\frac{2\pi d}{\lambda}\right) + 2\Gamma\cos(\Theta)} - \omega C_f Z_0\right) \qquad (5)$$

$$\varepsilon'' = \frac{\lambda}{2\pi d}\left(\frac{1-\Gamma^2}{1+\Gamma^2 - 4\Gamma\sin(\Theta)\left(\frac{2\pi d}{\lambda}\right) + 2\Gamma\cos(\Theta)}\right) \qquad (6)$$

3.2 Design of the probe

In order to perform measurements on large samples, a mechanical conical transition (Fig. 3) is specially designed to connect the coaxial cable to the sample holder which has an outer diameter of 70 mm.

The dimensions are calculated to maintain the characteristic impedance Z_0 at a value of 50 Ω along the conical section.

The top part, which constitutes the circular waveguide terminating the test circuit, can be removed after each measurement and then reused.

The chosen dielectric for the sample holder is Suter RTV16 silicone paste with a relative permittivity of 3 in the range of frequencies between 1 kHz and 3 GHz. It allows an easy unmolding of the concrete sample.

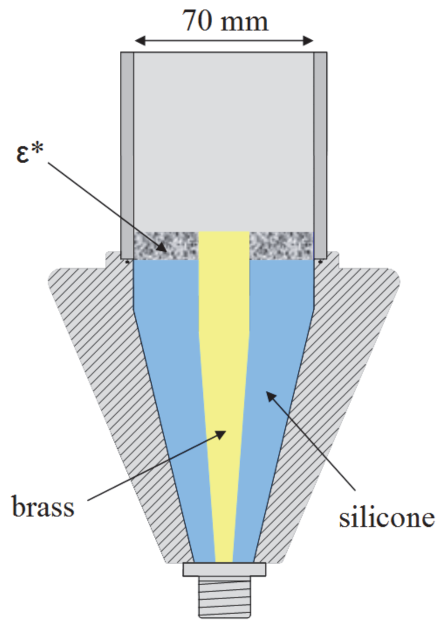

Fig. 3. Sectional view of the probe

The advantages of this design are:

- Easy computation of ε' and ε''
- Easy preparation of the sample : the concrete is cast directly in the probe
- Selectable material depth: the thickness of the sample can be adjusted thanks to screwed extending parts of the central conductor
- Reusable parts.

4. PERMITTIVITY MEASUREMENTS

The experimental setup is shown in Fig. 4: a ZVR Rhode & Schwarz network analyser is connected to the probe. The test set-up allows measurements of the reflection coefficient in the frequency range from 50 MHz to 4 GHz.

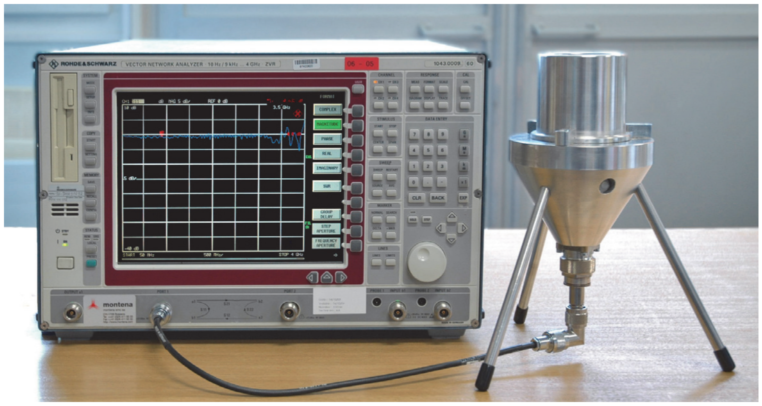

Fig. 4. Experimental setup

4.1 Calibration of the probe

For calibration, the top part of the probe is removed (see fig. 4 and 5). It is designed so that the calibration plane and thus the equivalent circuit of the sample holder correspond to the schematic of the Fig.1 and to the original design described in [5]. The calibration is successively carried out in short and in open circuit at the calibration plane level.

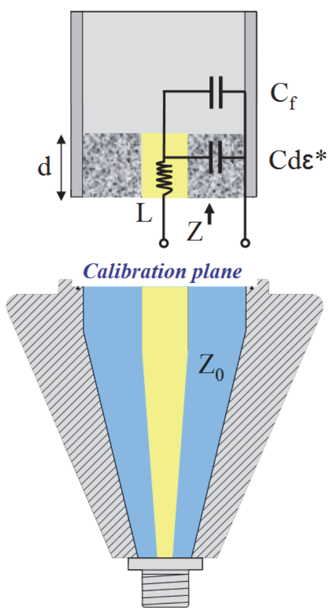

Fig. 5. Calibration plane and equivalent circuit of the sample holder

4.2 Verification with reference samples

The experimental setup is verified with a 10 mm thick Teflon (PTFE) reference sample.

Due to low accuracy in the determination of the phase Θ at low frequencies, the computed value of ε' does not match the theoretical value of 2.1 for frequencies under 50 MHz. However good accuracy is observed for frequencies up to 3 GHz (Fig. 6).

The imaginary part of ε^* could not be evaluated since the sensitivity of the test set-up is too low for low loss material as Teflon.

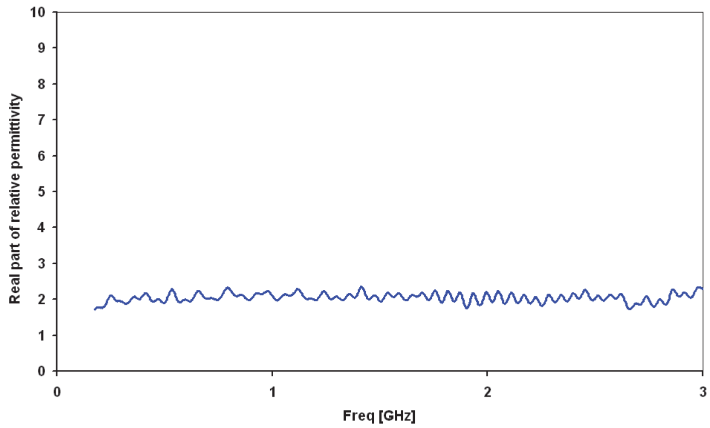

Fig. 6. Real part of the relative permittivity of a reference sample of Teflon

The measurement is also carried out on a Portland Norma 4 cement sample. The real part is given in the Fig. 7. The imaginary part varies from about 0.1 at 200 MHz to 0.005 at 2 GHz.

The Fig. 8 gives the result of measurement of the real part of the relative permittivity made on a sample of dry sand (0 to 4 mm diameter). The imaginary part is lower than 0.05 from 400 MHz to 2 GHz.

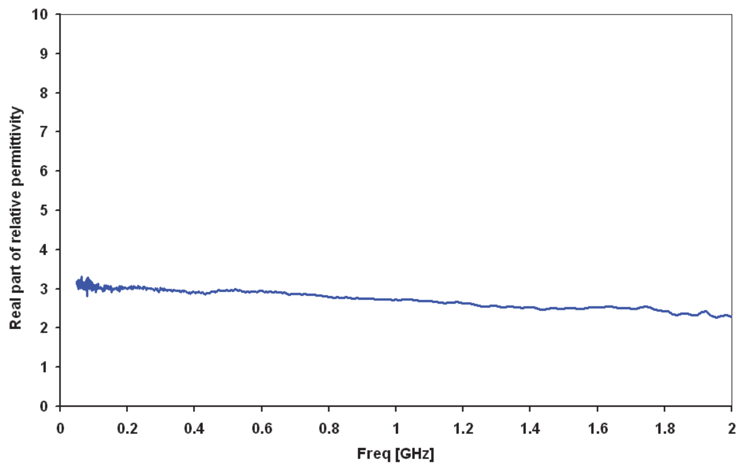

Fig. 7. Real part of the relative permittivity of a reference sample of Portland cement

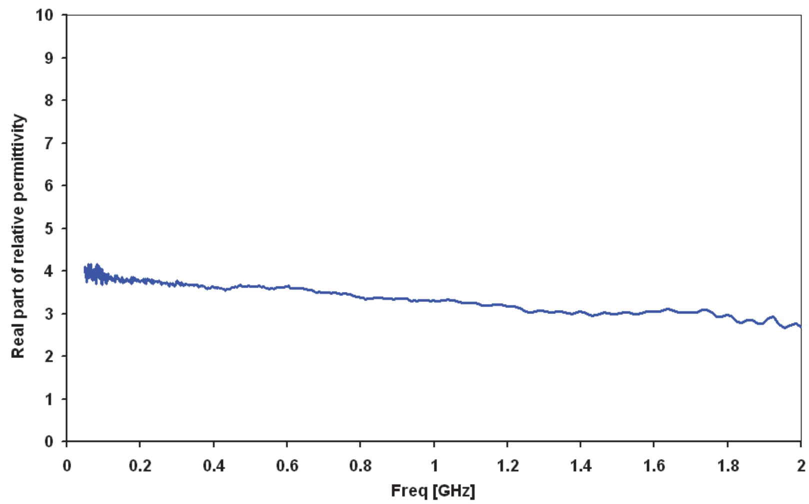

Fig. 8. Real part of the relative permittivity of a reference sample of sand

4.3 Measurements with concrete samples

A measurement is performed on a concrete sample with the following initial volume content: 11 % of Portland cement, 82 % of sand and small gravel (0 to 4 mm diameter) and 7 % of water. At t=0, the water content and the relative permittivity are maximal. The decrease of ε' as the hydration and curing process progresses is shown in the Fig. 9. The relative permittivity is stable after 96 hours.

Real concrete hardening requires more time than the duration of the presented measurements but the moisture content variation becomes very small so that no change of the dielectric properties was observed after 3 or 4 days.

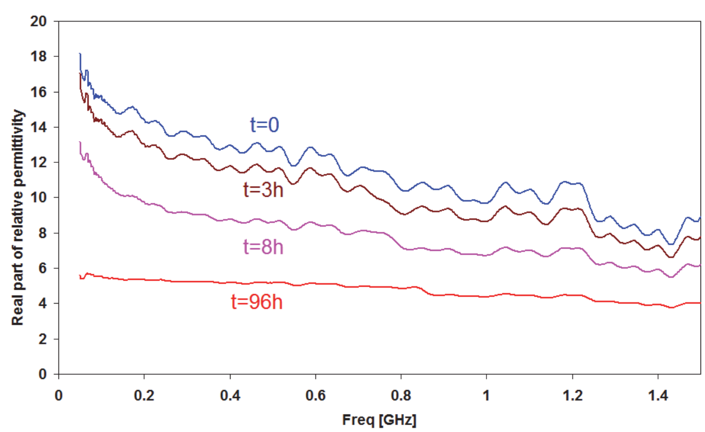

Fig. 9. Real part of the relative permittivity of a concrete versus frequency at various instants of time

Fig. 10 shows the imaginary part of the complex permittivity of the concrete sample. The losses are higher when the concrete is wet, and then they decrease as the concrete cures.

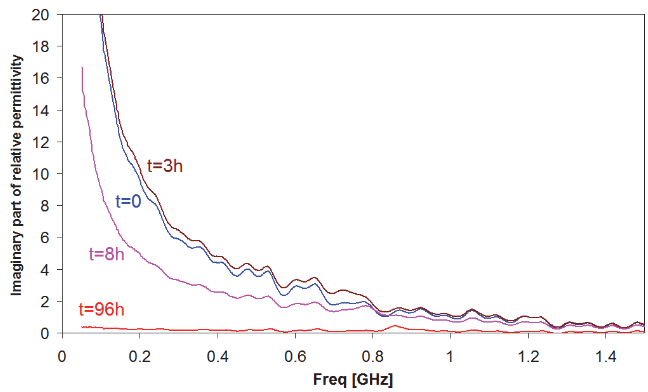

Fig. 10. Imaginary part of the relative permittivity of a concrete versus frequency at various instants

5. DISCUSSION

Due to the sample thickness of 10 mm, it is currently not possible to measure the permittivity of concrete with great heterogeneities (pebbles) so only mortars or cements could be investigated. But the influence of pebbles of material similar to sand and gravel is probably low. For thicker samples, a re-design of the probe is possible in order to achieve accurate measurements but the frequency range will be impaired.

6. CONCLUSION

The probe presented in this work was designed for the measurement of the dielectric properties of concretes, with a dielectric constant between 2 and 20 or more, for frequencies up to about 1.5 GHz.

Measurements of complex permittivity were performed on 70 mm diameter concrete samples for a frequency range 50 MHz - 1.5 GHz with values in good agreement with those presented in previous publications [3], [4], and [8]. An example taken from [4] is given in the Fig. 11.

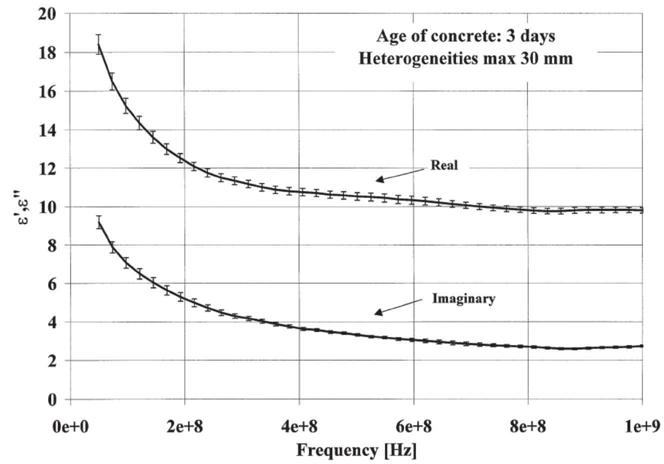

Fig. 11. Real and Imaginary part of the relative permittivity of a concrete versus frequency from [5]

Compared to other configurations, the open-ended coaxial probe opening into a circular waveguide presents the advantage that the samples do not need to be machined and the exceeding water can leave the concrete during the hydration process.
It also offers the possibility to monitor the dielectric properties of concrete in time, and to correlate them with environment variables such as moisture and/or temperature. It is particularly interesting for outdoor applications. In particular, it is possible to study the effects of meteorological phenomenon such as rain or snow on the interaction of electromagnetic waves on concrete buildings.

Different papers describe the relation between the permittivity parameters and the shielding attenuation of concrete walls. For instance in [9], calculations are made from examples of natural concrete without rebar and have shown a significant influence of the different moisture content.

7. Acknowledgment

Work performed by Montena Technology under contract from Skyguide.

8. References

[1] (2008) Geomodel website. [Online]. http://www.geomodel.com

[2] A. van Beek, K. van Breugel, M.A. Hilhorst, “Monitoring the hydration in LWA-concrete by dielectric measurements”, in Proceedings 5th International Symposium of High Strength/High Performance concrete, pp. 1007–1016, June 1999.

[3] B. Filali, J. Rhazi, F. Boone, and G. Ballivy, “Mesure des propriétés diélectriques du béton par une large sonde coaxiale à terminaison ouverte,” Canadian Journal of Physics., vol. 84, pp. 365–379, 2006.

[4] A. Robert, “Dielectric permittivity of concrete between 50 MHz and 1 GHz and GPR measurements for building materials evaluation,” Journal of Applied Geophysics., vol. 40, pp. 89-94, 1998.

[5] M.A. Stuchly, S.S. Stuchly, “Coaxial Line Reflection Methods for measuring Dielectric Properties of Biological Substances at Radio and Microwave Frequencies – A review”, in IEEE Transactions on instrumentation and measurement, vol. IM29, No. 3, Sept. 1980.

[6] P.I. Somlo, “The Discontinuity Capacitance and the Effective Position of a Shielded Open circuit in a Coaxial Line”, in Proceedings I.R.E.E Australia., pp. 7-9, Jan. 1967.

[7] S. S. Stuchly, J. Mladek, M.A. Stuchly and B. Parisien A method for the Measurement of the Permittivity of Thin Samples, Journal of Microwave Paper, 14(1), 1979.

[8] F. Thompson, “Measurement of moisture and permittivity in concrete samples during curing using microwave open transmission line techniques.” In: J.H. Bungey, Editor, Proceedings of Non-Destructive Testing in Civil Engineering, British Institute of NDT, Northampton), pp. 287–301, 1997.

[9] Ade Ogunsola, Ugo Reggiani, and Leonardo Sandrolini, "Modelling shielding properties of concrete", in 17th International Zurich Symposium on Electromagnetic Compatibility, 2006