Dielectric permittivity of concrete between 50 Mhz and 1 Ghz and GPR measurements for building materials evaluation

Antoine Robert *

Département de Génie de la Construction, École de technologie supérieure, 1100, rue Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

Received 3 February 1997; accepted 2 February 1998

Abstract

A new dielectric measurement device has been designed and constructed for permittivity measurement of concrete consisting of aggregates of up to 30 mm in diameter. The permittivity is measured in the frequency range 50 Mhz–1 GHz. The samples can be removed from the measurement cell and stored in controlled conditions. The dielectric constant of 0–30 aggregate concrete is measured as a function of hydration level and chloride content. Different mixing laws were compared with the measurements. This comparison shows that volumetric laws such as the complex refraction index model cannot fit the frequency variation and that the Cole–Cole model is the only acceptable one. The influence of chloride content on the permittivity of the concrete is measured and can be used to develop special GPR data processing for the location of salt ingress in civil engineering structures. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: dielectric permittivity measurements; concrete; mixing laws; chloride content

1. Introduction

Ground penetrating radar (GPR) is extensively used for non destructive testing of civil engineering structures and for material condition assessment. For example, it is used for bridge deck control (Parry and Davis, 1992; Weil, 1992; Chung et al., 1994) and reinforced concrete condition assessment (Halabe, 1990). Defects in the structure are detected and localized but interpretation enhancement is necessary in order to better use the information recorded and to define the limitations of the method. The extraction of material condition and localization of defects from radar measurements are related to the complex permittivity of the materials.

Experimental measurements of building materials permittivity have been reported only on cement paste or mortar, at frequencies outside of the range of GPR and usually only at a fixed frequency (Gorur et al., 1982; Otto and Chew, 1992; Perez-Pena et al., 1986). The lack of data on concrete with large heterogeneities in the frequency range of GPR has led us to the development of a new, large diameter transmission line.

As concrete is a porous and heterogeneous material, with pores filled with electrolytic solution, it can be expected that the relative permit-
tivity is frequency dependent. We observed this dispersion and used the experimental study to determine the best model describing the frequency variation measured.

One of the major defects in reinforced concrete is chemical attack. High chloride content of the concrete, due to deicing salt ingress, can induce the corrosion of rebars. The presence of chloride is assumed to introduce a great dispersion. We have measured the influence of the chloride on the permittivity of concrete.

Ordinarily, GPR interpretation assumes that subsurface interfaces will reflect replicas of the transmitted signal. If it is true in loss-less materials and can be approximately assumed when the medium is low-loss, it is no more acceptable when dispersion occurs. In that case, the interpretation based on the recognition of the returned signal and the measurement of the travel time delay will introduce significant errors (Annan, 1996). In some cases however, dispersion is not a limiting factor and can be used to extract information on the losses in the material.

2. Permittivity measurements

The choice of the sensor for measuring the complex permittivity of materials must take account of the broad frequency range of GPR, of the large size of the heterogeneities present in concrete (up to 30 mm in our case), of the fabrication of the samples and of the removal of the samples after the measurements for storing them in controlled conditions. A coaxial closed system has been chosen because the requirements can be satisfied, the fields are contained, the noise is minimized and the measurements are conducted by an automated network analyzer which yield the most accurate measurements.

Fig. 1 shows a schematic representation of the experimental setup. More details can be found in Shen (1985) or Coutanceau-Monteil and Jacquin (1993). The sample is machined to fit a hollow cylinder and is inserted in a coaxial line consisting of an inner and an outer conductor.

This line is connected to a S-parameter test set which sends a monochromatic electromagnetic wave and record the interactions with the sample. The permittivity is calculated from the complex reflection and transmission coefficients of the material. The improvement of this well known technique comes with the large size of the coaxial cell and the possibility of measuring the permittivity of materials with large heterogeneities like concrete.

We designed a large coaxial reflection/transmission cell with a sample volume of 2.24 see (Fig. 2). The large cell volume will serve to average the local fluctuations in permittivity inherent to the concrete structure. Details of design and calibration of the cell can be found in Robert (1997).

Samples of different types of concrete, mortar and cement paste have been fabricated and measured during approximately 1 yr. The data used here were recorded on five concrete samples denoted concrete 0–30 in the following. The maximum size of aggregate was 30 mm and the granulometry followed a normalized
distribution. The water/cement ratio was 0.55 and the cement content was 325 kg/m³. The samples have been cored and rectified to the requested dimensions 24 h after fabrication and stored in water for curing.

Fig. 3 presents typical measurements of permittivity of concrete 0-30 obtained with the cell 3 days after fabrication. This figure shows a large value at low frequency and indicates that both the real and imaginary parts of permittivity decrease with increasing frequency. This pattern of decreasing permittivity with increasing frequency was seen to be the case for all samples tested.

3. Frequency variation of permittivity

Concrete is a porous, heterogeneous material with pores partially filled with ionic solution. Halabe (1990) has modeled the complex permittivity and showed that real and imaginary parts are frequency dependent for a given temperature, salinity, porosity and saturation of the pores. Tsui and Matthews (1995) have also calculated the concrete permittivity with different mixing laws. Our experimental results are, as far as we know, the first measurements that can be compared to the theoretical models in order to choose which corresponds to the real material.

In this paper, we compare five models. The first three are homogeneous material models with frequency dependent permittivity. The last two are mixing laws which are often used for calculating the permittivity of heterogeneous materials.

For homogeneous materials, three possible mechanisms can be proposed to explain the dielectric dispersion: a Maxwell–Wagner effect enhanced by the presence of platy insulating particles, a polarization of double layer in the water near charged particles or a binding effect of water to solid surfaces so as to lower its dipolar relaxation frequency (Debye effect).

The variation of the permittivity as a function of frequency can be calculated by the relations:

$$\varepsilon(\omega) = \varepsilon_\infty - \left(1 + \frac{\varepsilon_\infty - \varepsilon_\infty}{1 + (i\omega\tau)^\alpha - i\frac{\sigma(0)}{\omega\varepsilon_0}}\right)^{-1}$$

(Cole–Cole, Maxwell–Wagner effect)

$$\varepsilon(\omega) = \varepsilon_\infty - \left(1 + (2i\omega\tau)^\alpha + i\omega\tau\right)$$

(double layer polarization)

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{\varepsilon_\infty - \varepsilon_\infty}{1 + (i\omega\tau)^\alpha} - i\frac{\sigma(0)}{\omega\varepsilon_0}$$

(Debye effect)

where:
- $\varepsilon(\omega)$: complex permittivity,
- $\varepsilon_\infty$: permittivity at low frequency,
- $\varepsilon_\infty$: permittivity at high frequency,
- $\omega = 2\pi f$: pulsation [Hz],
- $\tau$: relaxation time [s],
- $i = \sqrt{-1}$, $0 \leq \alpha$, $\beta \leq 1$,
- $\sigma(0)$: DC conductivity [S/m],
- $\varepsilon_0 = 8.85410^{-12}$ [F/m].

For heterogeneous materials, we used also CRIM (Complex Refraction Index Model) model which is frequently used for the calculation of the complex permittivity of a mixture from the data of the constituents. If the sample
is completely saturated, the permittivity is given by:

$$\sqrt{\varepsilon_{\text{mix}}} = (1 - \Phi)\sqrt{\varepsilon_{\text{mat}}} + \Phi \sqrt{\varepsilon_w}$$

(CRIM model)

where: \(\Phi\): porosity, \(\varepsilon_{\text{mix}}\): permittivity of the mixture, \(\varepsilon_{\text{mat}}\): permittivity matrix, \(\varepsilon_w\): permittivity water.

The permittivity of the water is a complex quantity calculated with the well known Debye relation and taking account of the DC conductivity of the electrolyte.

The other model has been proposed by Sen et al. (1981) and is a self similar model (SSC) of the permittivity of porous sedimentary rocks. Their aim was to avoid the percolation threshold inherent to the effective medium theory and not observed on experimental data. The SSC model is given by:

$$\left(\frac{\varepsilon_{\text{mat}} - \varepsilon_{\text{mix}}}{\varepsilon_{\text{mat}} - \varepsilon_w}\right)^{1/3} = \Phi$$

(SSC model)

From our measured values, it is clear that the frequency variation correspond only to the Cole–Cole empirical formula and that the other models showed a faster frequency transition (see Figs. 4 and 5).

Particularly, the CRIM model cannot be used for calculating the complex permittivity of the concrete. The reason is that the CRIM model is a function of the volume fraction but does not take account of the geometrical shape and orientation of the inclusions. The SSC model is also not able to fit the amplitude decrease and the frequency variation of the permittivity. It is probably because the SSC model assume that the inclusions are spherical.

The Cole–Cole model correspond to a symmetrical distribution of the relaxation time and have been applied to many experimental data. In concrete, the distribution of relaxation time can be explained by a Maxwell–Wagner effect enhanced by a non spherical inclusion effect.
4. Hydration of cement paste

Hydration of cement paste has an influence on the concrete measured. All the data showed a decrease of the permittivity as a function of the time since fabrication. This decrease is strong at the beginning of hydration and slow down after 28 days. Data recorded about 1 yr after fabrication indicated that hydration was not terminated but that the process had no more important effect on permittivity.

Fig. 6 shows $\varepsilon_{\text{stat}}$ and $\varepsilon_{\infty}$ vs. time of fabrication which are the results of fitting the experimental data with Cole–Cole model. The permittivity measurements are averaged on five samples.

Fig. 6 shows that the high frequency permittivity of the Cole–Cole model is constant and does not depend on the time since fabrication. At the contrary, the low frequency permittivity is strongly varying at the beginning of the measuring period and stabilize after a few weeks. After 250 days, the samples were used for measuring the chloride effect.

5. Effect of chloride content

The chloride content of the samples has been modified through saturation with NaCl solutions of different concentration. The concentration of the solutions has been calculated in order to correspond to chloride content measured on real concrete structures.

The Fig. 7 shows the influence of the salinity on the real permittivity of concrete 0–30. The concentration is indicated in gram per liter [g/l]. The 0 g/l concentration corresponds to the normal concrete salinity which is due to the ionic dissolution of cement and hydration components in water.

The 15.2 g/l correspond to the limit of tolerated chloride content in reinforced concrete under which the risk of corrosion is acceptable. The two higher concentrations were obtained on reinforced concrete where corrosion was visible.
Chloride content of concrete has a strong effect on permittivity, especially at the low limit of the frequency range investigated but chloride effect is negligible at 1 GHz. If high chloride content is intended to be detected with GPR, the measurements of permittivity show that it is necessary to use low frequency antennas. This is in contradiction with the current trend of using 1 GHz and higher frequency antennas in order to increase the resolution.

The permittivity can be represented as a function of the frequency divided by the conductivity (see Fig. 8).

It appears that the dielectric permittivity scales with frequency/conductivity. This has already been reported by Kenyon (1984) on calcite rock and is a strong indication that the dispersion of the permittivity is due to a texture effect. This geometrical influence of non-spherical inclusions has been suggested by Sen (1981).

6. Conclusions

Permittivity of concrete with heterogeneities up to 30 mm were measured with a new system. The values showed a decrease of both real and imaginary parts of the permittivity with increasing frequency. This variation can be fitted with the Cole–Cole model and indicates a texture effect. The evolution of the model parameters as a function of time has been measured.

The experimental data of concrete permittivity with high chloride content show that GPR can be used to detect chloride attack. They also show that the effect of chloride is important at low frequency but disappears at 1 GHz.

The measurements show that in concrete, the electromagnetic losses are important, especially in the lower part of the frequency range. These losses influence the reflection of the GPR signal and must be taken account when interpreting GPR data on civil engineering structures. The experimental data can be used for the calculation of the reflection coefficient between asphalt layer and concrete.

References


Weil, G.J., 1992. Non-destructive testing of bridge, highway and airport pavement. Fourth Int. Conf. on GPR, Rovaniemi, Finland, June 8–13, pp. 259–266.
学霸图书馆
www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：
图书馆首页  文献云下载  图书馆入口  外文数据库大全  疑难文献辅助工具