Construction and Building Materials 136 (2017) 237–245

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Development of a multi-linear quadratic experimental design for the EM characterization of concretes in the radar frequency-band

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HIGHLIGHTS

- This study focuses on EM characterization of 36 concretes using a specific design of experiment.
- Concrete parameters are aggregates, cement and water to cement ratio.
- EM measurements are done in a coaxial-cylindrical cell, at different GPR frequencies.
- The complex permittivity is defined by a multi-linear polynom.
- Results show the impact of each parameter on concrete permittivity.

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form 6 September 2016
Accepted 16 December 2016
Available online 20 January 2017

Keywords:
Electromagnetic properties
Permittivity
Concrete
Composition
Humidity

ABSTRACT

This study is focused on the electromagnetic characterization of concretes within the ground-penetrating radar frequency band. The evaluation of the complex dielectric properties is carried out in laboratory on 36 different concrete specimens defined by a specific experimental design. The composition parameters of the concrete mix design are the aggregate nature, the aggregate content, the cement nature, the cement content and the water to cement ratio (*W/C*).

The model of relative permittivity associated to the experimental design is a multi-linear polynomial of the 5 chosen material parameters. The exploitation of this set of data consists in a calculation level of the coefficients of this model independently for the real and the imaginary parts of the relative permittivity. This reveals the significant relationship between the dielectric properties and the composition parameters.

Raw results in terms of the real and imaginary parts of the dielectric permittivity along frequencies are presented for 36 different concretes in dry and saturated conditions and the sensitivity of the parameters are discussed.

1. Introduction

During the last decades, the evaluation of concrete structures using non destructive (ND) techniques has increased in such proportions that the ground-penetrating radar (GPR) has become one of the major technique [1–5]. Although this technique enables to give information on the internal geometries, such as rebar location or mapping the structure thickness or concrete defects, the recent researches have been oriented on the electromagnetic characterization of the material itself, for a more accurate ND evaluation of the surveyed structures [6,7].

This EM characterization on concrete mixes has been studied through three approaches, the first being performed on small samples using cells or opened probes [8–10], the second using GPR systems on homogeneous slabs in laboratory while studying the velocity, the attenuation or the frequency band of the radar waves [11–14], and the last one focused on the inversion of the GPR signals in order to retrieve the relative permittivity of the concrete slab [15–17]. And then the water content or the chloride content of concrete structures could be considered [16–18].

One of the recurrent questions related to EM characterization is the level of influence of every parameter (component, state and environment parameter) which could the considered as well as the objective as a bias of the survey [19,20].

The main results of these studies show that the relative permittivity is mainly sensitive to the volumetric water content [9,12,15] while increasing roughly linearly [6,10–11,14–16], that moisty

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http://dx.doi.org/10.1016/j.conbuildmat.2016.12.061

concretes present strong dispersion effects at low GPR frequencies while stabilizing at higher frequencies [8,10,16,21]. Chloride content affects the permittivity mainly on the imaginary part, often measured through the attenuation of GPR waves, and only at low frequencies on the real part [6,8,10–11]. At last, the effects of dispersion and the influence of chloride content vanish for dry concretes.

An innovative alternative to such studies is one of the most important methodology dealing with experiments in practical applications from whatever kind of fields, such as industrial, biomedical or sociatal, named the Design of Experiment (DOE). It is an applied statistical approach which characterize and optimize system performance, while working on the most influential parameters. It enables to reduce a full factorial design analysis by selecting representative points from the full factorial experiment in such a way that the points are distributed uniformly within the test range and thus can adequately represent the overall situation. Principles and examples can be found in [22–24], and although results are empirical they have been validated in numerous fields.

Thus, the global research program presented in this paper has been designed to systematically characterize concrete mix designs on a large frequency band, from 100 to 800 MHz, in order to evaluate their sensitivities on the corresponding EM properties and to quantify the contribution of the mix parameters to the real and imaginary parts of the relative permittivity (ε_r) thanks to a multi-linear quadratic experimental design.

Working at these different frequencies enable to study the impact of the dispersion behavior of the permittivity of concretes at low frequencies and the EM characteristics at high frequencies considering that they are stable on a large GPR frequency band (800 MHz being representative of this range).

2. Experimental multi-linear quadratic design

2.1. Principle

A specific experimental design is defined in order to minimize the number of concrete mixes while obtaining the statistical knowledge of the needed information [24]. The advantages of such an approach are the possibilities to deal with quantitative and non quantitative parameters – such as the petrographic nature of the aggregates – and to highlight the eventual interaction between parameters.

The general scope of a such experimental multi-linear quadratic design remains under the three following hypothesis:

- For each quantitative parameter, when two values are proposed the dielectric constant is supposed to evolve linearly between the chosen limits; for three values, the dielectric constant can have a quadratic behaviour between the lower and upper values;
- For qualitative parameters, the modelling is valid only for the proposed and studied qualitative parameters;
- The dielectric constant of the bulk material can be modelled as a multi-linear regression of the most effective parameters as shown in paragraph 2.3.

2.2. Chosen parameters

A polynomial model has been chosen because one of the aims of the study is to analyse the different effects of each component of the concrete mix design on complex permittivity. The most effective parameters and their limit values have been chosen by structural engineers in order to represent statistically the largest range of concrete mix designs used in civil engineering for reinforced concrete structures.

Some parameters are defined as qualitative, like:

- The nature of the aggregates (code *G*). The nature of siliceous or silico-calcareous aggregate, from the western region of France, correspond to different relative permittivities,
- The nature of the cement (code *B*) which includes the Portland cement CEM I and the same cement with an air-entraining (AE) agent, plus a blended cement CEM III,

The other interesting parameters are quantitative, and listed below:

- The coarse aggregate content (code *A*). The mass of coarse aggregates by the total mass of all aggregates has been chosen equal to 50% and 65%, which can frame classical bridge concrete mix design,
- The cement content (code *C*) is comprised between 350 kg/m^3, low limit, and 410 kg/m^3, high limit for classical bridge concrete mix design,

All the resulting composition parameters are given in Table 1. Moreover, Table A.1, presented in Appendix A, summarizes the concrete mix design related to the multi-linear polynomial experimental design.

In addition, the concrete samples were dried and saturated as explained in paragraph 3.2 in order to estimate the influence of the concrete mix design parameters under these conditions.

- The water to cement ratio (*W/C*, code *R*) is a quantitative parameter which modify the porosity. Since it is the most important durability indicator and since it would be useful to know if the permittivity varies linearly or quadratically with *W/C* or porosity, 3 values have been chosen *W/C* = 0.35 or 0.5 or 0.55.

2.3. Experimental multi-linear quadratic design theory and significance

In a DOE approach, when designing the permittivity of a mixing using a multi-linear quadratic model, few points must be clarified: the parameters are normalized (whatever their unit or their condition), a linear tendency is considered for 3 parameters at level 2 (here *G*, *A* and *C*), a quadratic possible effect of the parameter on the permittivity is authorized by the level 3 (here *B* and *R*), and finally, the possible interactions are defined by the product of parameters (the first order being defined by the product of two parameters, the second order by three, and so on). The physical interpretation of interaction is related to couple effects of 2 parameters on the permittivity (in particular, note that a mere shift of the permittivity does not reveal an interaction).

If we note $\bar{Y}$ the vector of the measured permittivities, $\bar{\bar{M}}$ the matrix of the parameters, $\bar{X}$ the vector of the coefficients weighing the effect of the parameters and $\bar{e}$ the fitting error vector, the corresponding general equation is defined as follow:

$$\bar{Y} = \bar{\bar{M}}\bar{X} + \bar{e} \tag{1}$$

The evaluation of the effect of each parameter on the permittivity (on the real part on the one hand and on the imaginary part on the second hand) is performed by the matrix inversion according to the following equation:

$$\bar{X} = \left(\bar{\bar{M}}^T\bar{\bar{M}}\right)^{-1}\bar{\bar{M}}^T.\bar{Y} - \left(\bar{\bar{M}}^T\bar{\bar{M}}\right)^{-1}\bar{\bar{M}}^T.\bar{e} \tag{2}$$

Considering for our current study 3 parameters at 2 levels and 2 parameters at 3 levels, presented in Table 1, a classical complete factorial design would lead to study $3^2.2^3 = 72$ concrete mixes.