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Determination of concrete water content by coupling electromagnetic methods: Coaxial/cylindrical transition line with capacitive probes

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Abstract

This paper deals with the development and the validation of an innovative, easy-to-use and on-site technique for determination of concrete water content. The on-site technique is the capacitive probe, able to characterize in situ dielectric media in the 30-35 MHz frequency band (around 33 MHz). For the evaluation of water content in various civil engineering structures, a calibration methodology has to be developed and is presented herein. It is based on the complex permittivity estimation of various dispersive concretes, which is carried out by a cylindrical coaxial electromagnetic (EM) transition line allowing the characterization in laboratory of material samples in a large GPR frequency bandwidth [50-600 MHz]. This methodology consists then on a coupling between the results of both the capacitive probes and the coaxial EM cell extrapolated at low frequency (33 MHz). The extrapolation procedure used to link physically the results of the two techniques is provided by the 4p-variant of Jonscher's model which is parameterized to obtain dispersion curves of the complex permittivity for very wide frequency bands. The methodology is checked by a parametric study that associates the 4p variant of Jonscher's model with the physical and hydric characteristics of the six concrete mix designs representing high performance and ordinary concretes at various hydric states. The surface testing results measured by capacitive probes on slabs are successfully compared to the extrapolated results obtained on cores.

Keywords

Durability; diagnosis; saturation degree; reinforced concrete; dielectric constant; permittivity; dispersion curves.

35 Highlights

- 36 • Methodology to get calibration curve linking water content and permittivity;
- 37 • Jonscher's model used to fit dispersion curves of complex permittivity;
- 38 • Experimental campaign on 6 various concretes at 4 water contents;
- 39 • Analysis of the results obtained by 2 electromagnetic NDT methods;
- 40 • Validation of the methodology coupling the 2 NDT methods.

41

42 1. Introduction

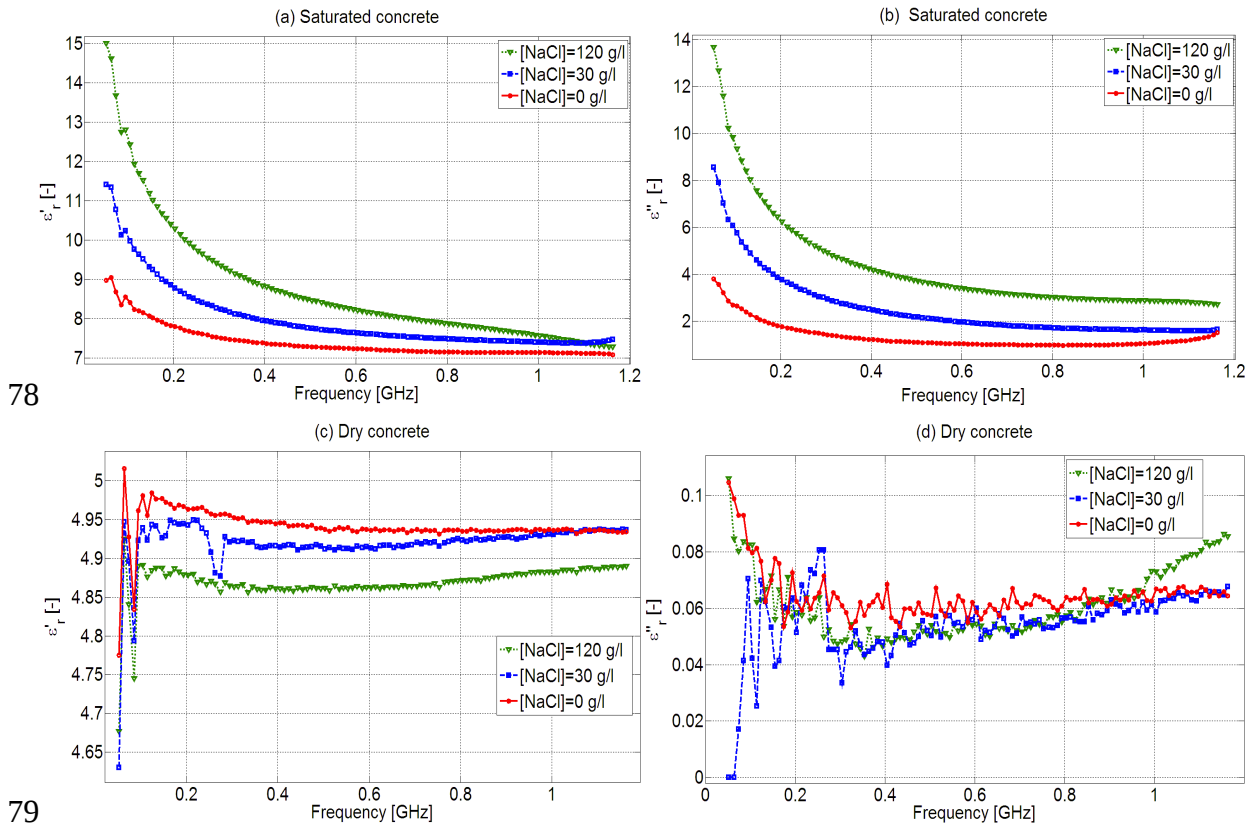
43 It is essential to determine the concrete water content of a reinforced concrete structure
44 in the context of sustainable structural preservation. Water content is namely a key factor,
45 first, to perform a diagnosis on concrete conditions and durability performances and, then, to
46 predict the residual service life of the studied reinforced concrete structure [1]. The non-
47 destructive testing (NDT) methods based on electromagnetic (EM) wave propagation are very
48 sensitive to the water content of concrete on the one hand and sensitive to the nature of the
49 mixing components (limestone or siliceous aggregates, cement, silica fume, blast furnace slag,
50 fly ash...) on the second hand [2-9]. Thereby, non-destructive testing techniques based on EM
51 wave propagation constitute a valuable means for monitoring the condition of concrete. For
52 non-magnetic materials, the wave propagation is entirely governed by their complex effective
53 permittivity, which reflects the interaction between propagating EM waves and the tested
54 material including the solid matrix and the porosity filled by air and by interstitial solution
55 containing different ions.

56 For this purpose, several techniques have been developed, with varying degrees of
57 success, in order to describe the frequency dependence of the dielectric permittivity of
58 geological and civil engineering materials [8-17]. This frequency dependence of complex
59 permittivity has introduced the notion of material dispersion [18, 19]. Generally speaking, EM
60 characterization measurements, done on a conductive dielectric, give a complex effective
61 permittivity ϵ_e^* , which encompass the polarization effects, characterized by atomic or
62 orientation polarizability, and the migration of free charge carriers that are ions and electrons.
63 Moreover, its frequency dependence reflects different polarization and conduction
64 mechanisms potentially related to the inherent material properties. For most of such
65 literature, the relative permittivity ϵ_r^* , defined by the ratio ϵ_e^*/ϵ_0 (where ϵ_0 is the permittivity
66 of free space), is used while defining the dielectric constant as the real part ϵ_r' , and the tangent

69loss $\tan \delta = \epsilon''/\epsilon'_r$. In the following, studies will be focused on ϵ'_r and ϵ''_r under the generic
70term dielectric permittivity.

71 Recent researches [8, 15, 17, 21] demonstrated the dependence of the complex
72permittivity to the water and chloride contents in concrete (Fig. 1) with a discrimination
73between the two effects according to the frequency bandwidth and the nature of the
74observable (real or imaginary part of the permittivity). In the example of Fig. 1, it is possible
75to quantify the effect produced by the presence of chloride ions in the range of very low
76frequencies.

77



78
79
80Figure 1: Frequency variation of the complex relative permittivity at various chloride contents for a concrete
81with $W/C=0.5$ and siliceous aggregates (C2) -a-b- Real and imaginary parts at the saturated state -c-d- Real and
82imaginary parts at the dried state [22].

83

84

85Unfortunately, using conventional methods for determining the dielectric properties of
86concrete in different conditions becomes not sufficient. As the evaluation of the water content
87is one of the main factors of the penetration of aggressive agents in concrete, thus, of the
88evolution of the durability of reinforced concrete structures, the study focuses on the
89volumetric water content of concrete.

90

91In this paper, we propose a methodology to evaluate the water content of concrete structures.
92The principle is based on the assessment of the complex permittivity carried out on a large
93frequency bandwidth. The methodology consists first on a coupling between the results of
94capacitive probes, able to characterize in situ dielectric media in the 30-35 MHz frequency
95band (around 33 MHz), and the ones of a coaxial/cylindrical transition line (also named EM
96cell). This EM cell enables to characterize material samples in the range [50 MHz - 600 MHz]
97in laboratory. The equations of the fitting dispersion curves are provided by the 4p variant of
98Jonscher's model [11, 16]. Moreover, it is shown here that the dispersion curves can be
99extrapolated on very wide frequency band [30-2000 MHz]. Thus, for each studied concrete
100mix design, a calibration curve linking the permittivity at 33 MHz with the water content can
101be established. It can then be used to transform the capacitive probes measurements into
102concrete water content. In the same way and in the same time, the dispersion curves can be
103used at high frequency corresponding to GPR to build the calibrations curves. The last will
104serve for subsequent nondestructive in situ investigation by ground penetrating radar (GPR).
105The whole methodology is validated thanks to a parametric study that associates the 4p-
106variant of Jonscher's model with the physical and hydric characteristics of six concretes with
107various mix designs representing high performance concretes, ordinary concretes and very
108porous concretes at various volumetric water contents.

109

110In the following Section II, the capacitive technique for on-site NDT evaluation of concrete
111structure conditions and the coaxial/cylindrical transition line used in the laboratory for
112calibration are presented. Then, in Section III, the general principle behind complex
113permittivity estimation in a wide bandwidth using the 4p-variant of Jonscher's model
114extrapolation will be described and validated on published data. In Section IV, the
115experimental protocol is summarized. Section V is devoted to the analysis of the validation
116results.. Lastly, conclusions are drawn in Section VI.

117

1182. The electromagnetic techniques used in this study

119

1202.1. Capacitive probes

121The principle of capacitive measurements is based on the calculation of the resonance
122frequency of an oscillating AC electric circuit (around 30-35 MHz) between the electrodes
123(Fig. 2), which are in contact with the upper face of the tested medium [23, 24].

124

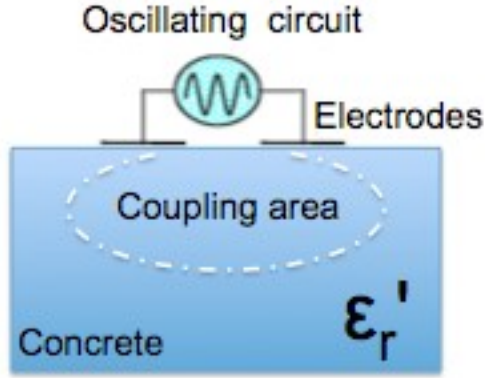


Figure 2: Capacitive probes -a- Schematic principle diagram -b- Photo of the device including several electrode sets.

This system forms a planar capacitor where the change in the capacitance C (F) is indicative of the dielectric nature of the medium components (*i.e.* the nature and the size of the aggregates, the water content, the chloride content ...). The change in the value of this capacitance involves a variation in the resonance frequency of the system f_{osc} following the relation:

$$f_{osc} = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{LK_{geo}\epsilon'_r}} \quad (1)$$

where L (H) is the system inductance, K_{geo} a geometric constant and ϵ'_r the real part of the relative equivalent permittivity of the coupling medium.

The volume investigated by the capacitive probes is highly dependent on the geometry of the electrodes. Four sets of electrodes (investigation depths equal to 2-3 mm for the small-size electrodes named PE, 2-3 cm for the medium-size ME and 8 cm for great-size electrodes GE which are stable, 5-6 cm for the set 3E which is optional and not stable) informs on the presence of any gradient according to depth. This device has been used to determine water content gradients in concrete [20, 21, 25]. It has also been adapted to study the filling of post-tension duct with cementitious grouts [26].

146 Considering equation (1), the relationship between f_{osc} and ε'_r can be effective only from the
 147 determination of the own system parameters. Obtaining these parameters is made via a probe
 148 calibrating protocol using standard materials.

149

150 Calibrating protocol

151 The objective of this calibrating protocol is to determine the parameters necessary for
 152 calculating the system capacitance from its resonance frequency f_{osc} , using slabs of standard
 153 materials (PVC, Teflon, marble, granite, limestone and eccostock) where the dielectric
 154 properties are well known. Equation (1) can be reformulated as:

$$155 \quad f_{osc} = \frac{1}{2\pi\sqrt{L(C_{mat} + C_{probe})}} = \frac{1}{2\pi\sqrt{LC_{probe}\left(1 + \frac{C_{mat}}{C_{probe}}\right)}} \quad (2)$$

156 In the case of civil engineering materials, we can admit that $C_{mat} \ll C_{probe}$.

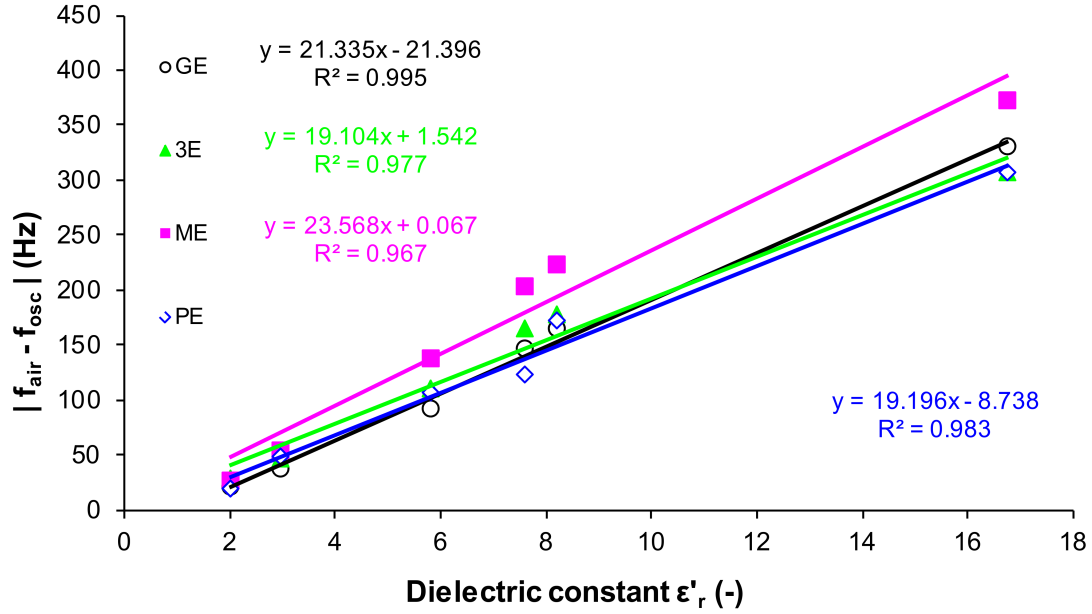
157 Following this, we perform an order 2 Taylor expansion of the function f_{osc} according to the
 158 variable C_{mat}/C_{probe} , which gives us:

$$159 \quad f_{osc} = A - \frac{A}{2} \frac{C_{mat}}{C_{probe}} \quad \text{where} \quad A = \frac{1}{2\pi\sqrt{LC_{probe}}} \quad (3)$$

160

161 This equation shows that the relationship between C_{mat}/C_{probe} and f_{osc} is linear. To reduce the
 162 interference effects due to the external environment of the system (temperature and humidity),
 163 the calibrating protocol requires a measurement in air f_{air} before any test on standard
 164 materials. Figure 3 shows the results for all the electrode sets. The values of the relative
 165 permittivity real part of standard materials are obtained via the EM cell measurements at
 166 100 MHz.

167



168

169 Figure 3: Results from the calibrating protocol of capacitive probes: oscillating frequency difference $|f_{air} - f_{osc}|$ vs
 170 the real part of the relative permittivity of standard materials.

171

172 For transposing the results expressed as real relative permittivity to results expressed
 173 as reference capacitance, we use equation (1). The determination of the geometrical parameter
 174 K_{geo} was performed by numerical modeling on Femlab® (developed by Comsol®) [14]. The
 175 results of this modeling are given in Table 1.

176

177 Table 1: Estimation of the geometrical parameter K_{geo} for various materials.

Material	Dimensions (mm ³)	Dielectric constant (-)	K_{geo} [-]		
			GE	ME	PE
Concrete	200×200×60		1.077	1.007	1.005
PTFE	200×200×60	2	0.923	0.975	0.991
PVC	200×200×60	2.95	0.923	0.975	0.991
Granite	600×600×153	5.8	1.0	1.0	1.0
Marble	300×300×100	7.6	1.011	1.008	1.0
Limestone	300×300×80	8.2	1.02	1.004	0.996
Eccostock	200×200×60	16.75	0.923	0.975	0.991

178

179 The determination of the coefficient $A = -80,6$ pF in equation (2) is carried out by identifying
 180 the coefficients of the linear regression of the oscillation frequency difference $|f_{air} - f_{osc}|$ as
 181 function of the permittivity. These results obtained on standard materials confirm those
 182 obtained on electronic circuit capacitors, despite a slight variation of the value of C_{probe} due to
 183 the effect of high permittivities (Eccostock) on the linearity of the regression functions.

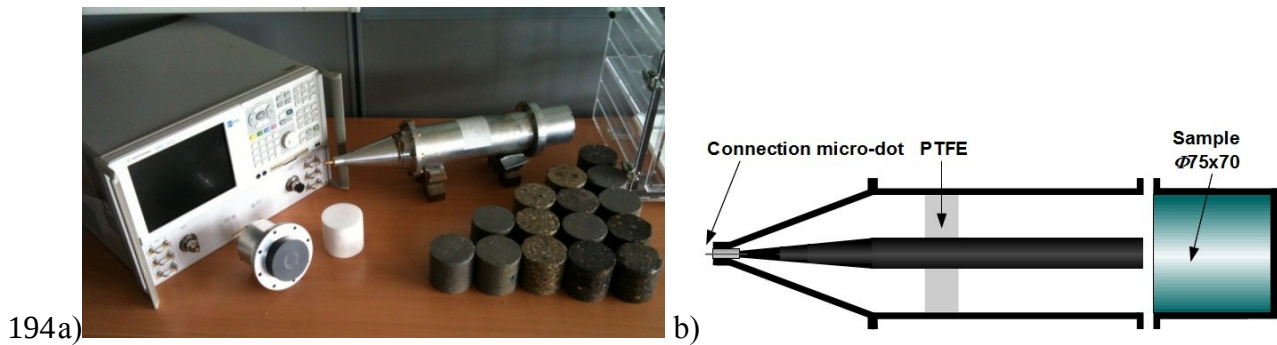
184 This calibrating protocol makes it now possible to determine the real part of the relative
 185 permittivity (also called dielectric constant) at 33 MHz with capacitive probes.

186

1872.2. Coaxial/cylindrical transition line

188The coaxial/cylindrical transition line (also named EM cell) was designed to measure
189complex dielectric permittivity of civil engineering rough materials at radar frequencies. It
190consists of a vector network analyzer, which is controlled by a central processing unit and
191connected to a cylindrical transition line via a coaxial cable [27]. The test sample is placed in
192a cylindrical waveguide holder connected to the coaxial line (Fig. 4).

193



195Figure 4 : Coaxial/cylindrical transition line (a) EM cell presented with the network analyzer and several
196concrete samples. (b) Scheme of the coaxial/cylindrical transition line.

197

198The dimensions of the cell ($\varnothing 75 \times 70$ mm) correspond to a volume greater than the Elementary
199Representative Volume of a heterogeneous mixture for a maximal diameter of aggregate
200 $D_{max} = 20$ mm.

201

202This EM cell enables measuring the permittivity of cylindrical samples of heterogeneous
203materials with large aggregate dimensions (up to 25 mm) over a frequency range from
20450 MHz to an upper limit, which depends on the value of the real part of permittivity. This
205latter frequency limit has been found to equal 800 MHz for all concrete mix formulations in
206dry conditions, then decreases for saturated concretes displaying high permittivity values.
207Beyond these values, resonance phenomena disturb the data analysis to a considerable extent.
208So we consider that the dispersion curve is obtained with confidence between 50 and
209600 MHz in this study. That is the reason why it is necessary to extrapolate the data obtained
210by the coaxial/cylindrical transition line on a large frequency bandwidth, at lower and greater
211frequencies to be able to link the results of all the in situ methods at the correct frequencies.
212Thereby, the 4p-variant of Jonscher's model [11, 16] constitutes an outstanding means to fit
213the permittivity dispersion curves on broad frequency bandwidth and to extrapolate the EM
214cell results at the required low frequency.

215

216**3. Frequency power law describing the dispersion curve of the complex** 217**permittivity: inversion-extrapolation procedure**

218

219**3.1. 4p-variant of Jonscher's model**

220Jonscher's model, which is also known as the universal dielectric response, is based on
221universality in the form of dielectric response. A variant that proved its validity for the EM
222characterization of concretes on large bandwidth is the four-parameter (4p) variant of
223Jonscher's model [11, 15]:

$$224 \quad \varepsilon_e(\omega) = \varepsilon_0 \chi(\omega) + \varepsilon_\infty - j \frac{\sigma_{dc}}{\omega} \quad (4)$$

$$225 \text{with} \quad \chi(\omega) = \chi_r \left(\frac{\omega}{\omega_r} \right)^{n-1} \left(1 - j \cot \left(\frac{n\pi}{2} \right) \right) \quad (5)$$

226

227where ε_∞ is the instantaneous dielectric response, σ_{dc} the direct current conductivity, χ_r the
228relative dielectric susceptibility and n the dispersion parameter, ω the angular frequency and
229 $j = \sqrt{-1}$. The reference angular frequency ω_r is arbitrary chosen.

230 Since the EM cell is limited to the minimum frequency of 50 MHz, while the
231capacitive technique is valid only around 33 MHz, then we developed a new method to cross
232the validity ranges of these two techniques. This method is based on the extrapolation of the
233coaxial/cylindrical transition line data using the 4p-variant of the Jonscher's model.

234

235**3.2. Extrapolation method: principle and validation on published data**

236Ihamouten et al. [16] showed that 4p-variant reveals no limitation over the whole
237coaxial/cylindrical transition line frequency range, as it follows accurately the permittivity
238variations. These results led us to invert the complex permittivity dispersion curve of the EM
239cell data using the 4p variant of Jonscher's model in order to extract the 4 parameters for a
240limited bandwidth.

241As observed in (4), the power-law behaviour of experimental data may be concealed by the
242presence of σ_{dc} in $\varepsilon_e(\omega)$ at low frequencies and by ε_∞ in $\varepsilon_e(\omega)$ at high frequencies. In theory,
243both of these disturbing influences can be removed by applying the Kramers–Krönig
244transformation. Mathematically speaking, the Hilbert transform of a constant is zero; thus, ε_∞
245is not included in the Hilbert transform of $\varepsilon_e(\omega)$ nor is σ_{dc} included in the transform of $\omega \varepsilon_e(\omega)$.

These considerations underscore the significance of the Kramers–Krönig transformation in the processing and interpretation of experimental data. To this end, we propose herein a computationally efficient two-step procedure for estimating the four model parameters. The first step consists of estimating the first pair of parameters (χ_r, n) from the Hilbert transform H of $\varepsilon_e(\omega)$ and $\omega\varepsilon_e(\omega)$ via a nonlinear optimization of the following cost function:

$$C(\chi_r, n) = \min_{\chi_r, n} \left[\Im \left[H \left(\varepsilon_e^{model} - \varepsilon_e^{expe} \right) \right] + \Im \left[H \left(\varepsilon_e^{model} - \varepsilon_e^{expe} \right) \right]^2 \right] \quad (6)$$

where \Im and H denote the imaginary part and the Hilbert transform, respectively. For the second step, each of the ε_∞ and σ_{dc} terms can be estimated as the solution to a simple linear least-squares problem, as follows:

$$\varepsilon_\infty = \frac{1}{N} \sum_{i=1}^N [\varepsilon'_e(\omega_i) - \varepsilon_0 \tilde{\chi}'(\omega_i)] \quad (7)$$

$$\sigma_{dc} = \frac{\sum_{i=1}^N \omega_i^{-1} [\varepsilon''_e(\omega_i) - \varepsilon_0 \tilde{\chi}''(\omega_i)]}{\sum_{i=1}^N \omega_i^{-2}} \quad (8)$$

where N is the number of frequencies and where $\tilde{\chi}'$ and $\tilde{\chi}''$ are the estimated real and imaginary parts of the susceptibility $\tilde{\chi}$ (4). The two-step procedure has provided nearly the same fitting error and parameter values as the more computationally demanding minimization of the following cost function:

$$C(\chi_r, n, \varepsilon_\infty, \sigma_{dc}) = \min_{\chi_r, n, \varepsilon_\infty, \sigma_{dc}} \left| \varepsilon_e^{model} - \varepsilon_e^{expe} \right|^2 \quad (9)$$

For this reason, the two-step procedure is preferred. Using the parameters $[\chi_r, n, \varepsilon_\infty, \sigma_{dc}]$ extracted from equation (9), we estimate the frequency variation of ε_e on a large bandwidth using equation (4).

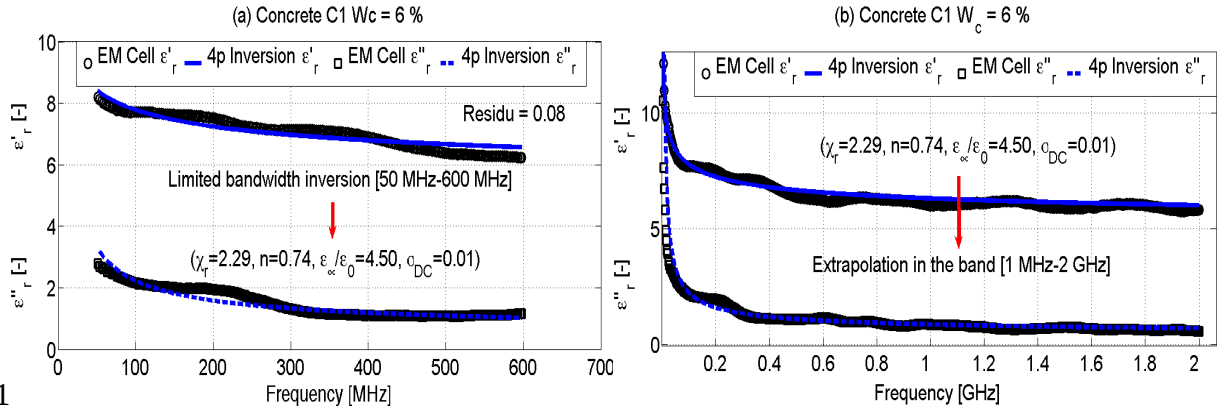
Extrapolation method validation on published data

Since the determination of the complex permittivity of our coaxial/cylindrical transition line is limited to the minimum frequency of 50 MHz, we used for this validation published experimental data [28], obtained by the EM characterization of two concretes (volumetric water content $W_c = 6\%$ and 9%) in the frequency bandwidth [1 MHz-2 GHz].

This validation procedure begins with the EM cell data inversion on the band [50 MHz- 600 MHz] (Figs 5a and 6a), allowing the extraction of the parameters $[\chi_r, n, \varepsilon_\infty,$

275 σ_{dc}]. Then we proceed to the rebuilding of the complex permittivity curves on the band
 276 [1 MHz-2 GHz] with the substitution of the parameters $[\chi_r, n, \epsilon_\infty, \sigma_{dc}]$ in equation (4) (figures
 277 5b and 6b). We can see through the results of figures 5a and 6a that the 4p-variant of
 278 Jonscher's model perfectly fits the experimental data in the case of the two studied concretes,
 279 although the inversion frequency bandwidth is narrow.

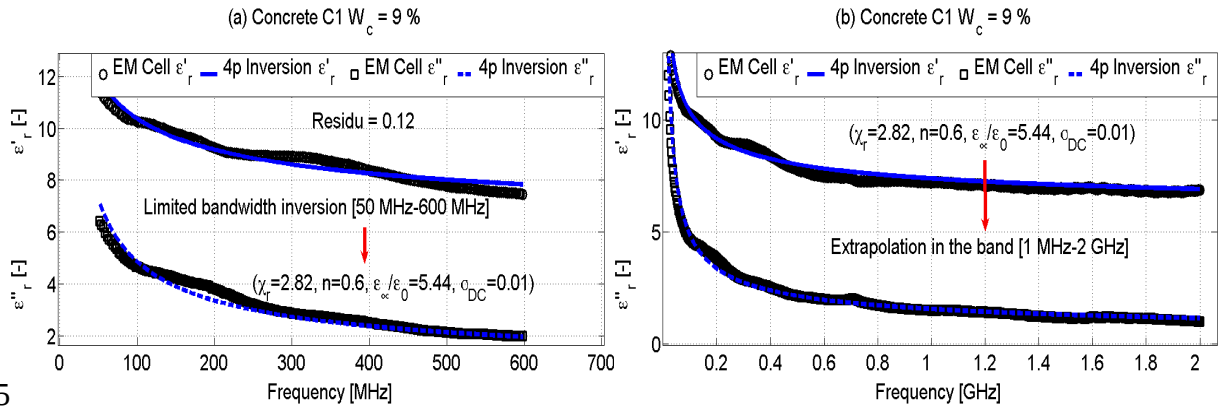
280



281

282 Figure 5: Extrapolation of the EM cell data (concrete C1, water content $W_c = 6\%$ [26]) from the frequency band
 283 (a) [50 MHz - 600 MHz] to the frequency band (b) [1 MHz - 2 GHz], using the 4p-variant of Jonscher's model.

284



285

286 Figure 6: Extrapolation of the EM cell data (concrete C1, water content $W_c = 9\%$ [26]) from the frequency band
 287 (a) [50 MHz - 600 MHz] to the frequency band (b) [1 MHz - 2 GHz], using the 4p-variant of Jonscher's model.

288

289 The results of figures 5b and 6b show that the broadband extrapolation via this Jonscher's
 290 model variant perfectly obeys the dielectric behavior of the two concretes, even for very low
 291 frequencies. This result is also confirmed by the low value of the normalized residues (Figs 5
 292 and 6) calculated as follow:

293

$$residue = \frac{1}{N} \sum_{i=1}^N \left| \epsilon_{e_i}^{model}(\omega_i) - \epsilon_{e_i}^{expe}(\omega_i) \right|^2 \quad (10)$$

294

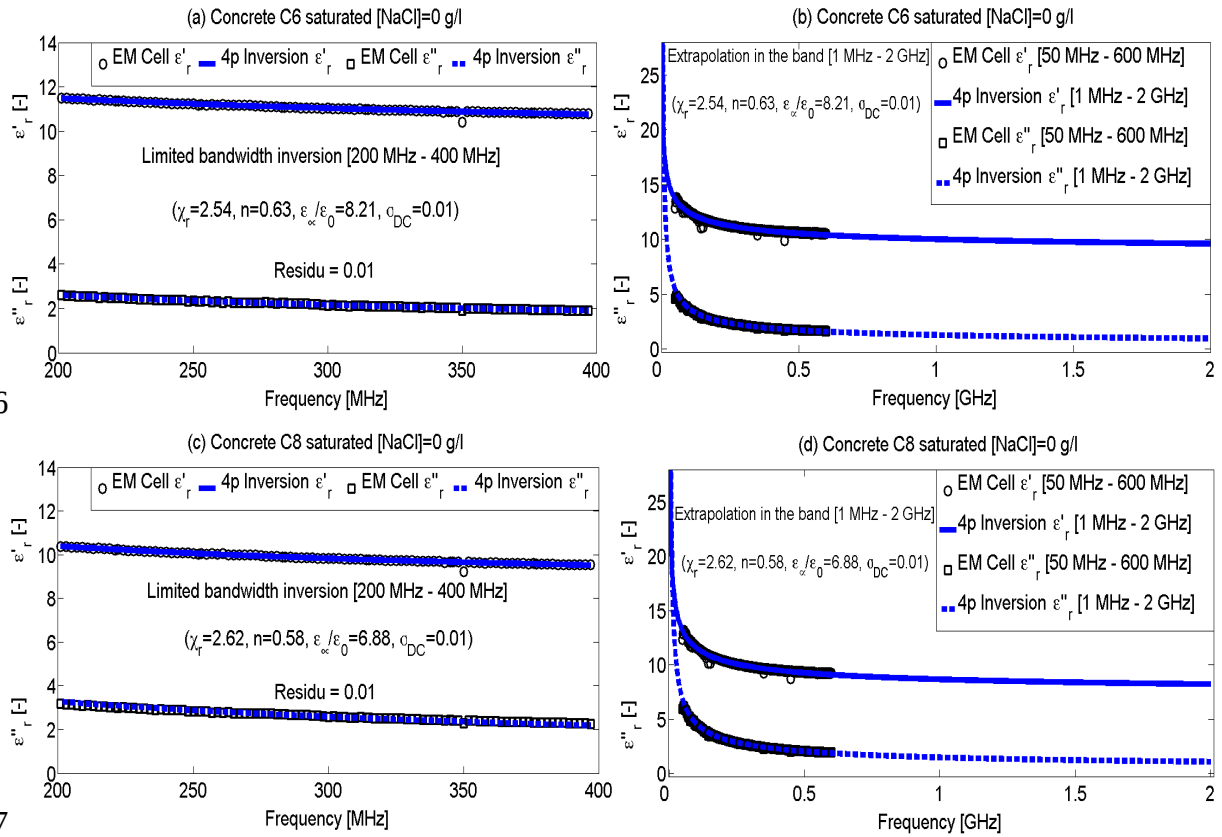
To go further in this validation, we tested the sensitivity of this extrapolation procedure in front of the low frequency effects of Maxwell-Wagner phenomenon [29]. This phenomenon is related to the ionic nature of the concrete interstitial solution. To do this, we applied this extrapolation procedure to concrete C6 and C8 (Table 2) presented in detail further in the paper.

300

Two cylindrical test samples (75×70 mm) corresponding to each of the studied concretes were saturated under vacuum [28] with salty water at [NaCl] = 0 g/L and [NaCl] = 120 g/L [20].

Figures 7 and 8 include firstly the results of the coaxial/cylindrical transition line characterization of the two concretes and secondly, the results of the extrapolation procedure.

305



307

Figure 7: Extrapolation of the EM cell data for concretes C6 (a-b) and C8 (c-d) saturated with water [NaCl]=0 g/L from the frequency band [200 MHz - 400 MHz] (a-c) to the frequency band [1 MHz - 2 GHz] (b-d), using the 4p-variant of Jonscher's model.

311

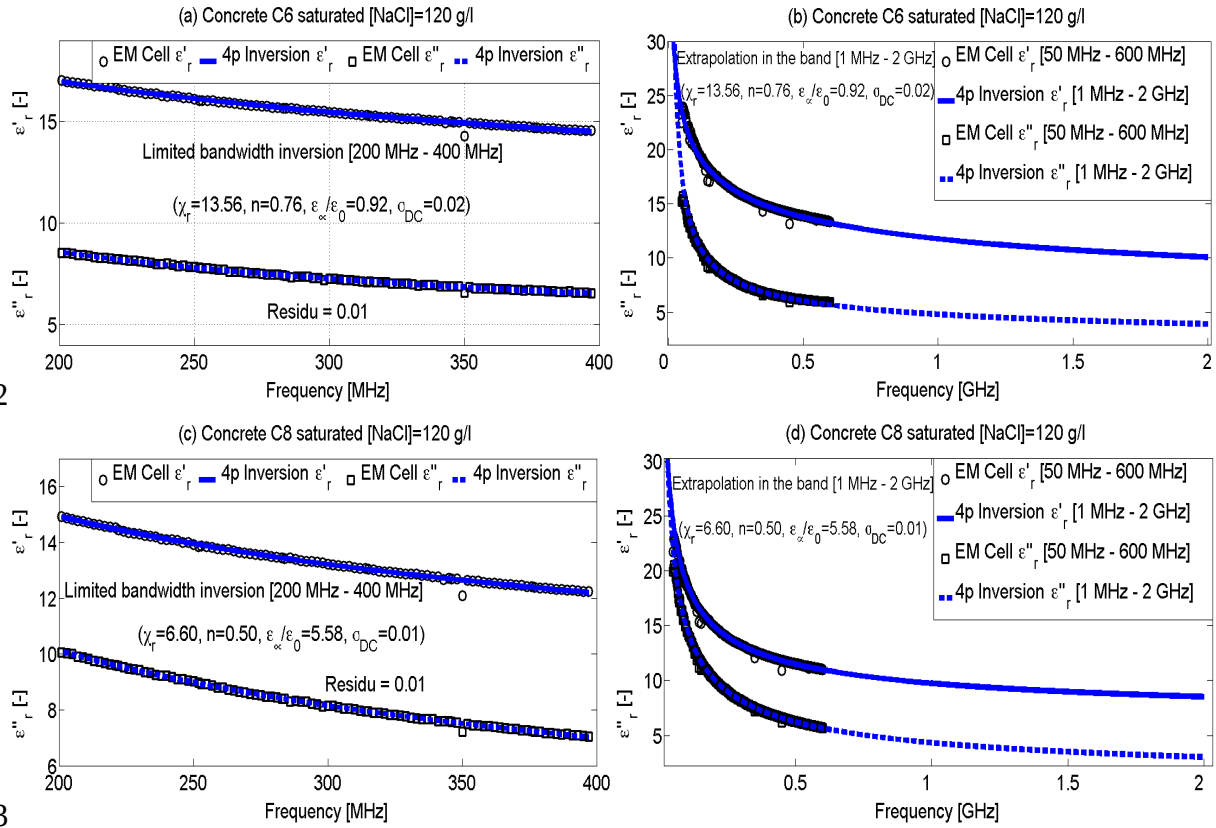


Figure 8: Extrapolation of the EM cell data for concretes C6 (a-b) and C8 (c-d) saturated with salt solution [NaCl]=120 g/L from the frequency band [200 MHz - 400 MHz] (a-c) to the frequency band [1 MHz - 2 GHz] (b-d), using the 4p-variant of Jonscher's model.

We note that the extrapolation method using the 4p-variant of Jonscher's model allows an accurate estimation of the complex relative permittivity in a frequency domain where the inversion does not occur to estimate the four parameters, *ie* [50 MHz - 200 MHz]. This result demonstrates also the robustness of this method in front of the changes in the material characteristics. Indeed, the presence of chloride ions into concrete pore solution in no way disturbs the estimation of the complex relative permittivity at low frequencies, despite the presence of the effects of the Maxwell-Wagner's phenomena. We can deduce from these results that our extrapolation method is able to take into account physical phenomena affecting in general the dielectric behavior of concrete.

In conclusion, the development and the validation of this extrapolation method allow us to expand the frequency validity domain of the coaxial/cylindrical transition line measurements. This result implies the possibility to compare the EM cell results with those of the capacitive probes at the frequencies 33-35 MHz.

3344. Experimental protocol

335

336The six concretes of this study have been originally designed for the electromagnetic
337characterization of hydraulic concretes through a quadratic experimental design [9]. The
338composition parameters of the mix design are the nature of the aggregates, the nature of the
339cement, the cement content, the water to cement ratio (W/C) and the quantity of coarse
340aggregates. The minimum number of concretes, required to obtain the statistically valuable
341information about these mix parameters, is equal to 36 [9].

342Here, six concretes, made with the same Portland cement and the same proportion of coarse
343aggregates (Table 2), are selected for the present study. The porosity, measured by water
344saturation under vacuum [30], is ranging from about 8 to 16%.

345For each concrete, a beam has been cast and, after curing and hardening, sawn into slabs and
346cored. So, for each mix, we dispose of 3 slabs (300x300x70 mm) for capacitive measurements
347and 3 cores ($\varnothing 75 \times 70$ mm) for the EM cell.

348

349Table 2: Concrete mix design and porosity measurement results

Concrete name	Water to cement ratio	Portland cement* CEM I	Coarse aggregates (4/20)	Fine aggregates (sand 0/4)	Type of aggregate**	Porosity
	$W / C (-)$	(kg/m ³)	(kg/m ³)	(kg/m ³)		(%)
C6	0.35	350	1301	715	silico-calcareous	11.1±1.4
C8	0.35	410	1212	652	siliceous	10.1±1.9
C18	0.5	350	1192	642	siliceous	15.0±3.5
C20	0.5	410	1125	619	silico-calcareous	15.9±1.7
C30	0.55	350	1163	626	silico-calcareous	15.4±2.3
C32	0.55	410	1074	578	siliceous	15.8±2.4

350* Portland cement CEM I 42,5R Anneliese Heidelbergcement Group

351** Siliceous aggregates of Palvadeau, silico-calcareous aggregates of Boulonnais

352

353 As the aim is to study the water content influence, all the samples have been carefully
354conditioned and controlled. They have been saturated under vacuum then dried at $T=70^{\circ}\text{C}$
355step by step until they reach the mass corresponding to the aimed saturation degrees which are
356 $S=100\%$, 75%, 50% and $\sim 3\%$. They are then submitted to an homogenization process before
357non-destructive testing. The homogenization process of the water content is based on Parrott's
358method [31] which consists in wrapping the sample in tight adhesive aluminium foils and
359keeping it in the oven during the same time as the drying process duration, so during 2 weeks

360minimum. Note that one slab per aimed saturation degree is used, whereas 2 cylindrical
361sample per aimed saturation degree are tested, for each concrete.

362 At each step, when the aimed saturation degree is reached and the sample water
363content distributed homogeneously, the cylindrical samples are tested in the EM cell and the
364slabs with capacitive probes.

365 At the end of this experimental campaign, all the samples are dried in an oven at
366105°C to reach a dry state and be able to calculate the real saturation degrees or the real
367volumetric water content of each step a posteriori according to the standard protocol [30].

368

3695. Results and Analysis

370 In this paragraph, the results of the experimental campaign are presented and the
371extrapolation methodology is applied. Then, the comparison of the measured and extrapolated
372permittivities makes it possible to validate the methodology.

373

3745.1. Capacitive results as a function of the water content

375 Capacitive measurements have been carried out on slabs conditioned in laboratory
376until they reach a homogeneous saturation degree. The aimed saturation degrees are 100%,
37775%, 50% and 0% but the results presented here refer always the real volumetric water
378contents.

379

380 Figure 9 presents the capacitive measurement results obtained on concrete slabs at
381different water contents. As the dielectric constant is sensitive to the aggregate nature, the
382results for concretes mixed with silico-calcareous aggregates are separated from the ones
383mixed with siliceous aggregates. These results show that the dielectric constant is linearly
384correlated with the volumetric water content in accordance with literature results obtained on
385other mix designs [20]. We obtained similar results with all the electrode sets. The constant
386value of the linear regression is smaller for the concretes with siliceous aggregates than for the
387ones with calcareous aggregates.

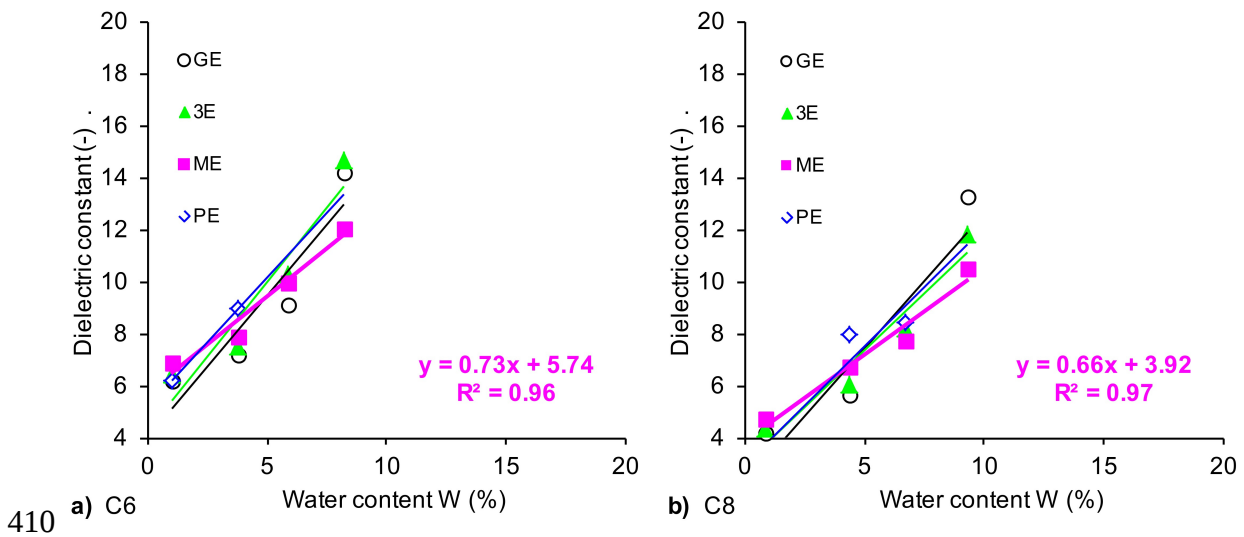
388 Let's note that the variability of the results is mainly due to the material dispersion. It
389would be reduced by averaging the results on several slabs instead of studying only the mean
390result on only one slab per aimed saturation degree. Meanwhile the dispersion is relatively
391small and the regression coefficient valuable.

392

3935.2. EM Cell results as a function of the water content

394 For the six concretes, two cylindrical samples par mix were studied at four aimed
 395saturation degrees $S = 0\%$, 50% , 75% and 100% in the coaxial/cylindrical transition line.
 396Thus, for each concrete, the tests provided 8 real volumetric water contents and 8 dispersion
 397curves thanks to the EM cell. An example of dispersion curve for concrete with $W/C = 0.5$ and
 398siliceous aggregates is shown in Fig. 1. The other dispersion curves of the complex
 399permittivity vs frequency obtained are not presented here. They are used to fit the 4p-variant
 400of the Jonscher's model, between 200 and 400 MHz, which provides thus the extrapolated
 401complex permittivities at 33 MHz. Fig. 7 shows the results for the concretes C6 and C8 in
 402saturated conditions.

403 Figure 10 gathers the complex permittivity at 33 MHz obtained on concrete cylindrical
 404samples at different volumetric water contents, for the real and imaginary parts. As in Fig. 9,
 405the results for concretes mixed with silico-calcareous aggregates are separated from the ones
 406mixed with siliceous aggregates. As for capacitive probes results, EM cell results show that
 407the dielectric constant is linearly correlated with the volumetric water content in accordance
 408with literature results obtained on other mix designs [20] and that the constant of the
 409regression curve is smaller for mixes with siliceous aggregates.



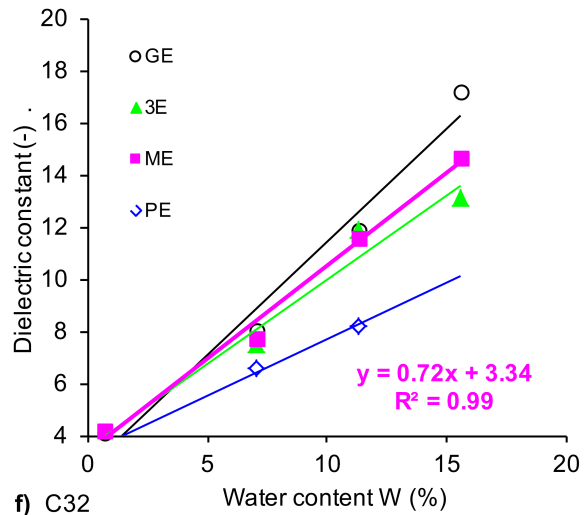
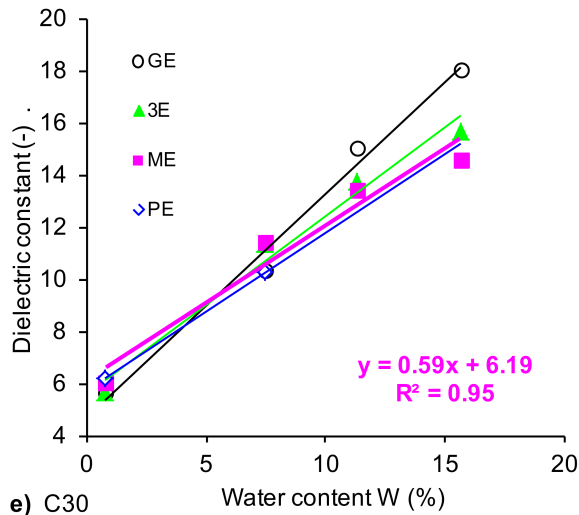
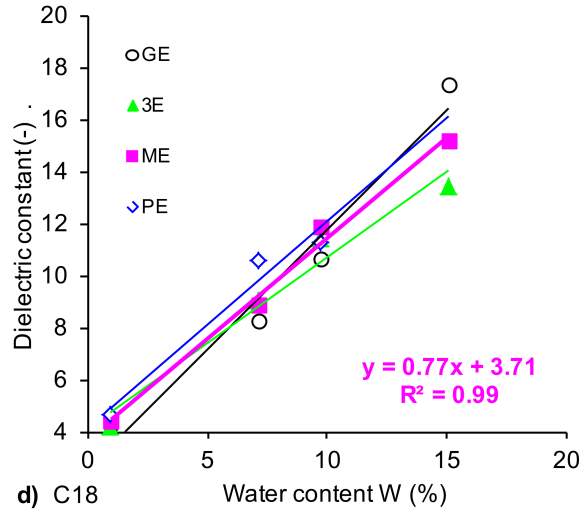
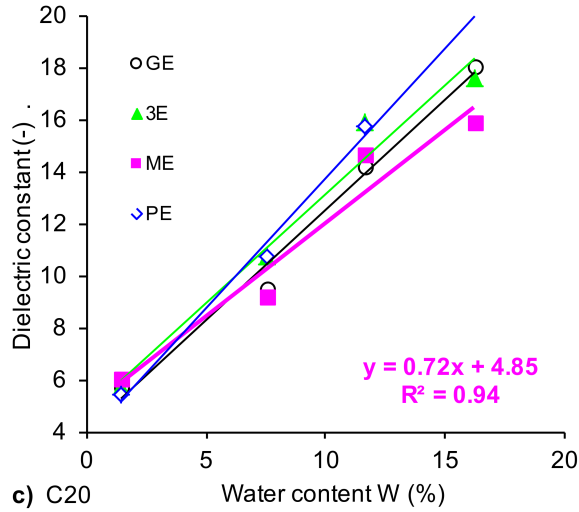
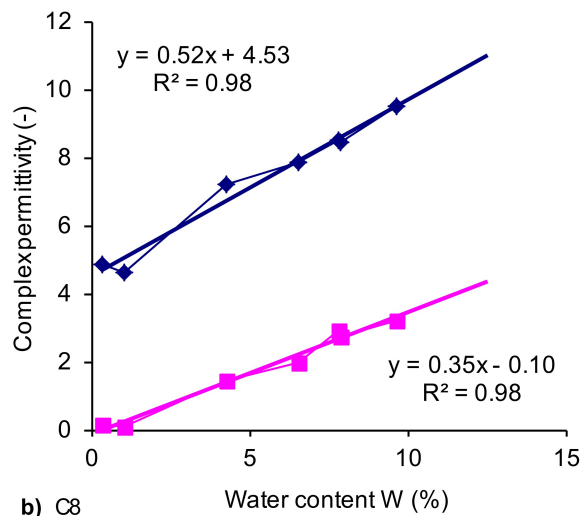
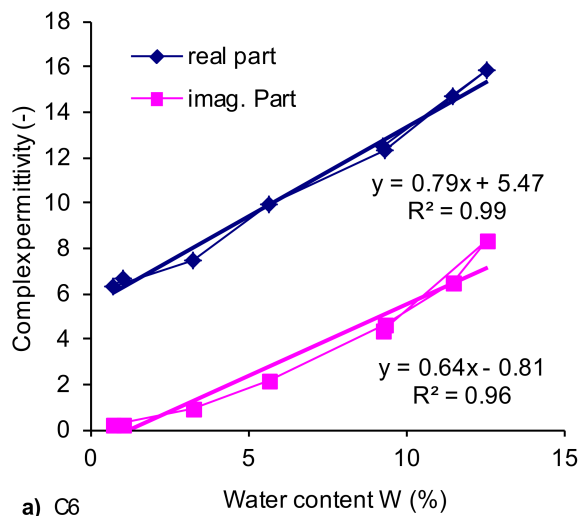
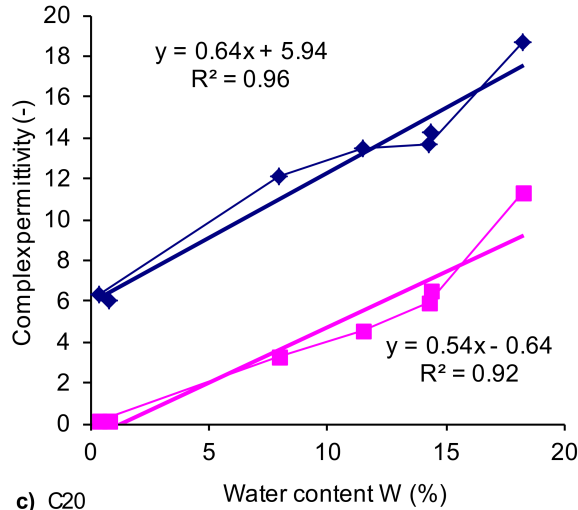
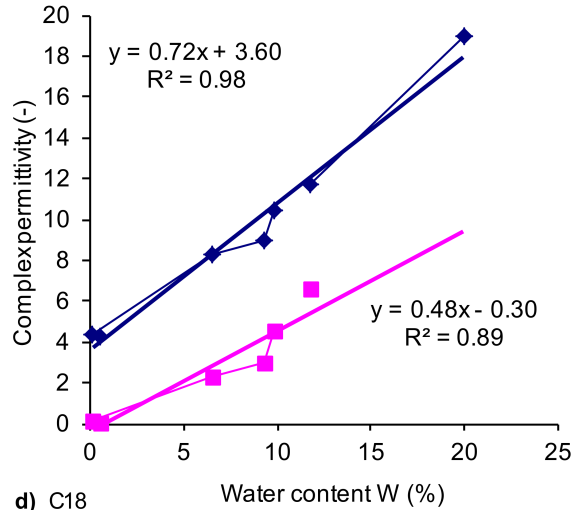


Figure 9: Capacitive results on slabs (with 4 electrode sets) function of the volumetric water content – a,c,e) Silico-calcareous concretes – b,d,f) Siliceous concretes.

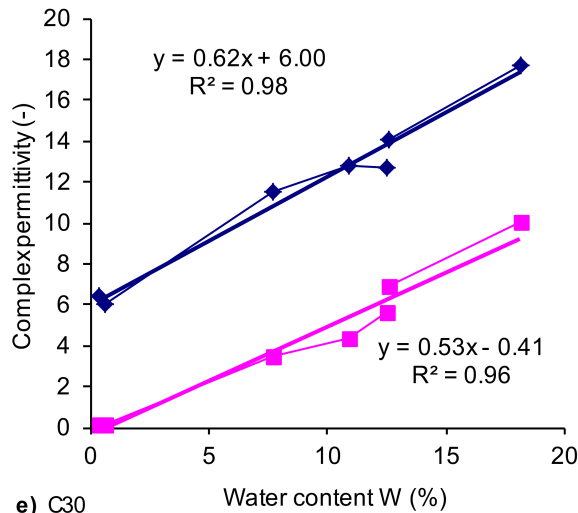




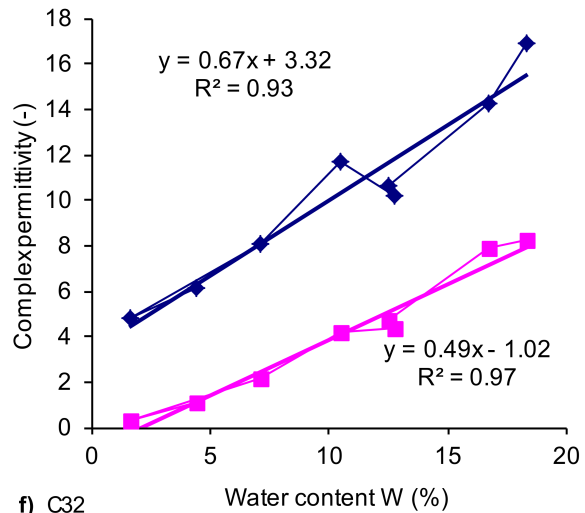
417 c) C20



d) C18



418 e) C30



f) C32

419 Figure 10: EM cell results on cores, extrapolated to obtain the complex permittivity as function of the
420 volumetric water content – a,c,e) Silico-calcareous concretes – b,d,f) Siliceous concretes.

421

422 5.3. Comparison between capacitive measurement results and complex permittivity 423 obtained by extrapolation at 33 MHz

424 The 4p-variant of the Jonscher's model was used to fit the dispersion curves of each
425 concrete cylindrical sample at each water content then they were extrapolated at 33 MHz. The
426 extrapolated real parts of the complex permittivity at 33 MHz are now compared to the results
427 of the capacitive probes performed on slabs in similar hydric conditions but not exactly the
428 same.

429 Figure 11 make it possible to compare these extrapolation results to the capacitive
430 measurement dielectric constant at 33MHz. We notice that the extrapolated data are plotted
431 (stars) without making the difference between concrete mixes to simplify the figure. This is

possible because only the quantity of cement and the quantity of water varies for these mixes, not the nature of the components.

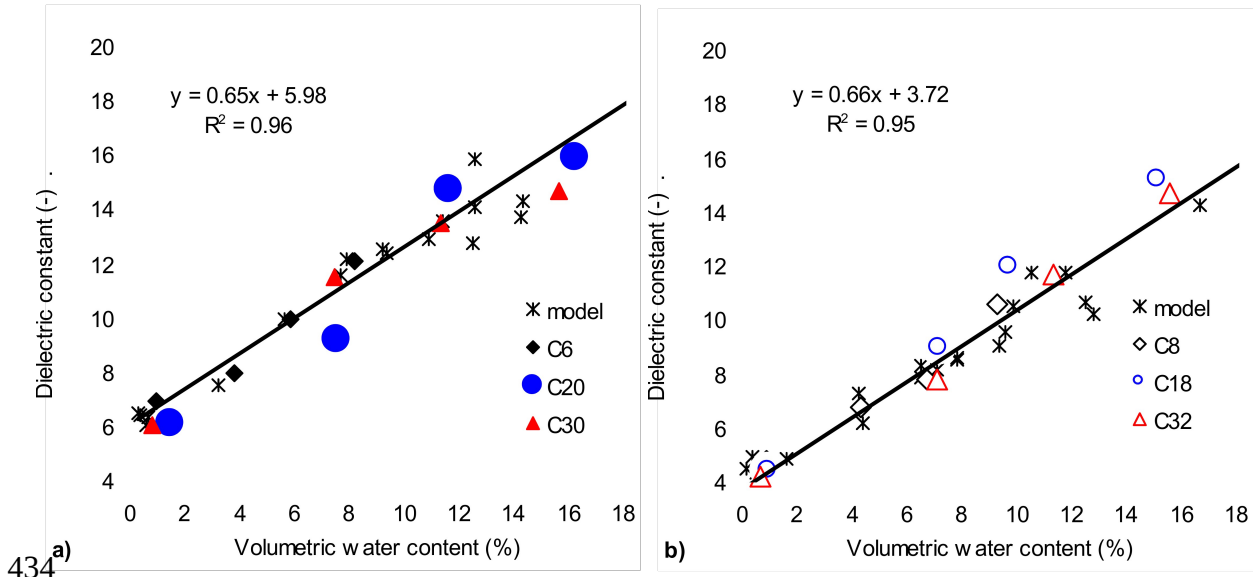


Figure 11: Comparison of the Jonscher's model extrapolation with the capacitive results at 33MHz– a) Siliceous concretes – b) Siliceous concretes

These figures 11a and 11b show the very good correspondence between all experimental data and extrapolated data for each type of aggregate. They also highlight the capability of the Jonscher's model to link the results of the both methods studied at low frequency. Tables 4 and 5 show the regression coefficients for every measurement and extrapolation as functions of the water content. It is interesting to see through these results that the linear trend of the variation of the complex permittivity in function of the water content is always verified even after the EM cell extrapolation procedure. Furthermore, the comparison between the linear regression parameters of tables 4 and 5 shows that the best matches between the EM cell extrapolation data and those of the capacitive probes are obtained, nearly for all concretes, using the ME electrodes. The correlations remain excellent, above 95 % with one exception (concrete C20), and decrease as the porosity increases. This could be explained by the higher variability of the extrapolated measurements when the volumetric water content becomes important.

Table 4: Real and imaginary parts of the complex permittivity ϵ at 33 MHz obtained on cores by the EM cell and extrapolated with Jonscher's model: linear regressions function of the volumetric water content $\epsilon = aW + b$

Concrete name	Real part ε'			Imaginary part ε''		
	Slope a	Constant b	Correlation coeff. r^2	Slope a	Constant b	Correlation coeff. r^2
C6	0.79	5.47	0.99	0.64	-0.81	0.96
C8	0.52	4.53	0.98	0.30	-0.10	0.98
C18	0.72	3.60	0.98	0.52	-0.30	0.89
C20	0.64	5.94	0.96	0.54	-0.64	0.92
C30	0.62	6.00	0.98	0.53	-0.41	0.96
C32	0.67	3.32	0.93	0.49	-1.02	0.97

454

455Table 5: Dielectric constant or real part of the permittivity ε at 33 MHz obtained on slabs by the 4 different

456capacitive probes: linear regressions function of the volumetric water content $\varepsilon = aW + b$

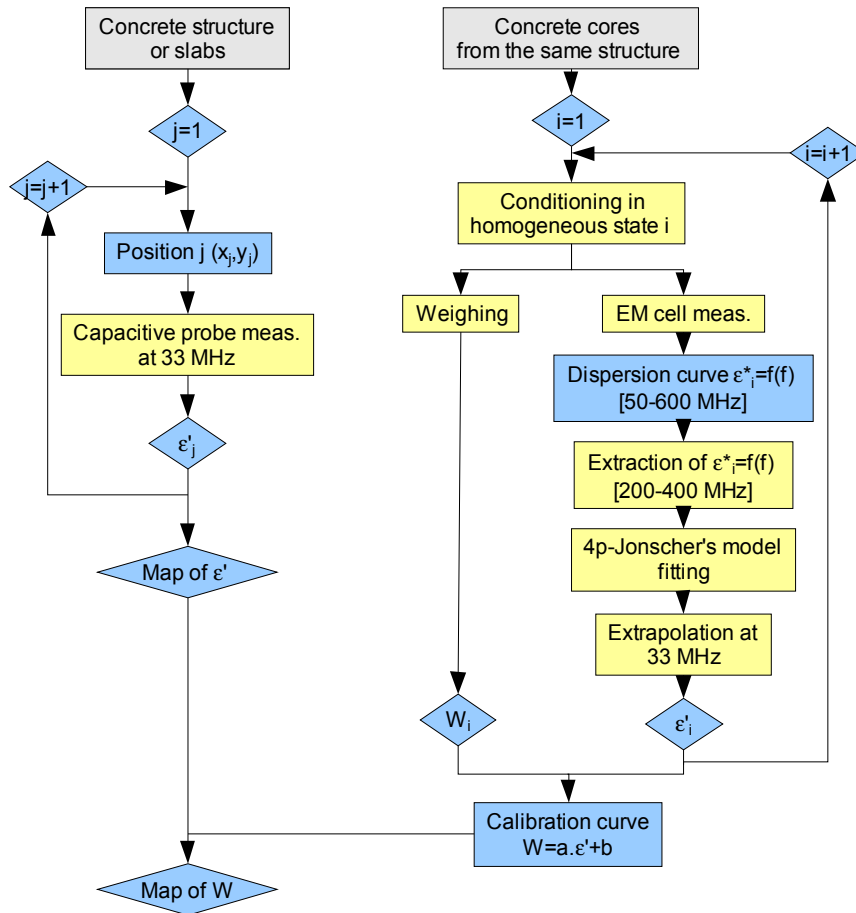
Concrete name	Electrode size	33 MHz		
		Slope a	Constant b	Correlation coeff. r^2
C6	GE	1.08	4.09	0.86
	3E	1.14	4.33	0.91
	ME	0.73	5.74	0.96
	PE	0.99	5.19	
C8	GE	1.03	2.25	0.87
	3E	0.87	2.97	0.94
	ME	0.66	3.92	0.97
	PE	0.91	2.96	0.90
C18	GE	0.92	2.55	0.97
	3E	0.66	4.08	0.97
	ME	0.77	3.71	0.99
	PE	0.79	4.13	0.96
C20	GE	0.85	4.02	0.99
	3E	0.84	4.76	0.97
	ME	0.72	4.85	0.94
	PE	1.00	3.74	0.99
C30	GE	0.86	4.71	0.99
	3E	0.68	6.61	0.98
	ME	0.59	6.19	0.95
	PE	0.92	4.91	0.93
C32	GE	0.87	2.78	0.97
	3E	0.65	3.48	0.97
	ME	0.72	3.34	0.99
	PE	0.43	3.35	1.00

457

458 At this step of the study, we can consider that the coaxial/cylindrical transition line
459associated with the Jonscher's extrapolation constitutes a valuable means to obtain the in-lab
460calibration curve relating the dielectric constant with the water content on cores before any *in*
461*situ* measurements on real structures using the capacitive probes. Let us note also that this
462methodology, summarized in the flow-chart of Fig. 12, was employed to get the calibration
463curves and to benefit of the capacitive probes ability to determine the dielectric constant at

different depths to obtain the water content profiles inside concrete slab in a non-destructive way [32, 33].

466



467

468Figure 12: Flow-chart of the methodology to evaluate and map the water content of a slab or an element of a real
469concrete structure

470

4717. Conclusion

472 In this paper, we used the 4p-variant of the Jonscher's model as a means to rely the
473results obtained by two EM testing methods, although their validity ranges are different. An
474extrapolation procedure was developed and validated for the estimation of the complex
475permittivity at very low GPR frequencies. The whole methodology is detailed in this paper.

476 The complex permittivity dispersion curves are determined on cores in a
477coaxial/cylindrical transition line for the characterization of six concrete mixes at four
478different degrees of saturation. In parallel, concrete slabs are conditioned in the same way as
479cores to reach homogeneous degree of saturation, and then tested by the capacitive technique
480using few electrodes of different sizes. The comparison of the capacitive results and the fitted
481dielectric constant is very satisfying.

482 As a consequence, we can consider that the coaxial/cylindrical transition line
483 associated with the Jonscher's extrapolation constitutes a valuable means to obtain the
484 calibration curve relating the dielectric constant at 33 MHz with the water content on cores.
485 For higher frequencies, from 0.8 to 2 GHz, in the GPR frequency range, the same
486 methodology could be applied to get the calibration curves useful for GPR on site testing in
487 the same time without extra coring. Thus, as a perspective, the capacitive technique,
488 combined with GPR in situ measurements, could enable us to accurately characterize cover-
489 concrete complex permittivities and thus the cover concrete water content or degree of
490 saturation of a real reinforced concrete structure.

491

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497

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