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1 **Evaluation of chloride contamination in concrete using electromagnetic non-**
2 **destructive testing methods**

3 Xavier Dérobert^{1*}, J.F. Lataste², J.-P. Balayssac³, S. Laurens³

4 ¹LUNAM université, IFSTTAR, CS4, 44344 Bouguenais, France

5 ²University of Bordeaux, I2M, 33 400 Talence, France

6 ³LMDC, INSA/UPS Génie Civil, 135 Avenue de Ranguel, 31077 Toulouse cedex 04 France

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8 **Corresponding author:** *xavier.derobert@ifsttar.fr*

9 *Ifsttar, route de Bouaye, CS4, 44344 Bouguenais, France*

10 *Tel: +33 (0)2 40 84 59 11 Fax: +33 (0)2 40 84 59 97*

11 **Abstract**

12 We present the results of the sensitivity of some electromagnetic non-destructive testing
13 (NDT) methods to chloride contamination. The NDT methods are resistivity, using a
14 quadripole probe, capacitive technique, with few sets of electrodes, and radar technique,
15 using different bistatic configurations. A laboratory study was carried out involving
16 three different concretes with different water to cement ratios. The concretes were
17 conditioned with different degrees of NaCl saturation by means of three solutions
18 containing 0 g/L, 30 g/l or 120 g/l. The solution was homogenized in the concrete by
19 using a specific procedure. Results show that the EM techniques are very sensitive to
20 the chloride content and saturation rate and, on a second level, to the porosity. Multi-
21 linear regression processing was performed to estimate the level of sensitivity of the
22 NDT measurements to the three indicators. Values of ten ND observables are presented
23 and discussed. At last, the uncertainties of the regression models are studied on a real
24 structure in a tidal zone.

25 **Keywords:** radar, resistivity, capacitance, humidity, concrete, chloride, measurement

26 uncertainty

27 **1. Introduction**

28 Chloride-induced corrosion is one of the major causes of degradation of reinforced
29 concrete structures, considering marine exposure conditions or the extensive use of de-
30 icing salts in many countries. Reliable assessment of existing structures is based on the
31 knowledge of chloride concentration values, as the residual service life is estimated
32 from the time required to reach the chloride threshold value at the depth of the
33 reinforcement [1-3].

34 Although the destructive characterization of chloride content is now fully applied all
35 over the world, it is widely recognized that the procedure is cumbersome and requires a
36 lot of time, and that any non-destructive technique able to provide this information
37 would bring an appreciable improvement to the assessment methodologies [4]. The
38 complexity of the diagnosis is partially due to the multiple influences included during
39 the measurement and the inversion process, all of which act as sources of uncertainty in
40 the diagnosis. Generally, to assess an indicator (e.g. chloride content), all other
41 properties are assumed to be constant. This assumption is either justified – and the
42 diagnosis is accurate – or false – but the approach is still used for lack of another
43 solution. The latter case is the more frequent, which is why improvements to NDT
44 methods and interpretation methodology are long overdue.

45 Numerous studies have shown the great potential of electromagnetic (EM) techniques,
46 including electrical ones, for the evaluation of concrete durability indicators, such as
47 water content, chloride content and, to a lesser extent, porosity [5-12]. These studies,
48 performed on different concrete mixes, have shown the high level of sensitivity of the
49 EM observables (from conductivity to relative permittivity at radar frequencies) to these

50 durability indicators.

51 A national project gathering six academic partners and six industrials, the “Strategy of
52 non-destructive evaluation for the monitoring of concrete structures” (SENSO) project,
53 aimed to propose a methodology for the non-destructive evaluation of some indicators
54 related to the durability of concrete by means of a combination of numerous non-
55 destructive testing (NDT) methods, including electrical, EM and ultra-sonic (US)
56 techniques [13]. For each indicator, the objectives were to evaluate its value (average
57 and degree of variability) and to estimate the degree of reliability of this evaluation. An
58 important experimental study was carried out on controlled samples (homogeneous
59 regarding the variation of indicators inside the samples) and a large database was built
60 up and explored to draw relationships between NDT measurements and indicators [13-
61 16]. Saturation rate, porosity, carbonation depth and chloride ingress were the indicators
62 addressed for 8 different concrete compositions, and were investigated with more than
63 11 ND methods.

64 Within that framework, a specific experimental programme was dedicated to chloride
65 content, and the objective of this paper is to present the results of that study. Laboratory
66 experiments were carried out on three different concretes using three saturation degrees
67 of solutions involving two concentrations of NaCl (30 and 120 g/l). The quantities of
68 total chloride were assessed by chemical titration and NDT measurements were
69 performed at the same time. As US techniques showed very low sensitivity to chloride
70 content, only the electrical and EM techniques are presented and discussed below.

71 In this paper, the objective of the first study is to determine multilinear regressions
72 between ND measurements and specific indicators: saturation rate, porosity and
73 chloride content, for various depths, on controlled concrete samples. The second part

74 studies the use of these regressions to estimate chloride content, also addressing the
 75 question of uncertainty at the levels of methods and models. Then, the last part is
 76 devoted to their implementation on a real site in a tidal zone. The discussion only
 77 focuses on the choice of techniques for chloride contamination diagnosis here, and on
 78 the uncertainty levels.

79

80 2. Experimental design

81 2.1. Preparation and conditioning of concretes

82 Focusing on chlorides, three concretes were made using the same cement (CEMI 52.5 N
 83 from Calcia) and the same nature of aggregates (round siliceous) from the River
 84 Garonne. The details are presented in Table 1, keeping the same references as those used
 85 in the SENSO project [13]. For each mix, 11 slabs (50x25x12 cm) were cast and water
 86 cured for 28 days. Three of these slabs were devoted to assessment of the porosity, the
 87 compressive strength and the characterization of the Young's modulus.

88

Table 1. Concrete characteristics

Aggregates	Round Siliceous (0/20 mm)		
	G1	G3	G8
Reference			
W/C	0.30	0.55	0.80
Cement (kg/m ³)	405*	370	240
28 day strength (MPa)	72.9	43.8	20.2
Density (kg/m ³)	2541	2457	2405
Porosity (%)	12.5	15.5	18.1

89

* addition of 45 kg/m³ of silica fume

90 The other 8 slabs were contaminated with different concentrations of chlorides. After
 91 drying at 80°C until their weight became constant, 4 slabs were contaminated by
 92 absorbing a solution of water containing 30 g/l of NaCl (CL-1) at three different
 93 saturation degrees (one slab at 40%, one slab at 80% and two slabs at 100%). The other

94 4 slabs were contaminated with a solution of water containing 120 g/l of NaCl (CL-2) in
95 the same conditions of saturation. After absorbing the quantity of salt water
96 corresponding to a given saturation degree, each slab was sealed in a polyethylene sheet
97 and adhesive aluminium foil.
98 They were then placed in an oven at 80°C for three months to homogenize the
99 interstitial solution. Before the contamination with chlorides, the slabs were conditioned
100 at 5 different levels of saturation (0, 40%, 60%, 80% and 100% of tap water) and tested
101 with NDT methods in the same conditions as for chloride contamination (CL-0). Thus it
102 was possible to compare the effect of chloride contamination on NDT measurements on
103 the sample samples. Table A1, in appendix, summarizes the saturation rate for all the
104 concretes, the porosity (measured on only 1 slab) and the total chloride content in
105 percentage weight of dry concrete, assessed by chemical titration at different depths (5,
106 10, 15 and 20 mm). It can be seen that there was no significant chloride gradient over
107 the depth investigated by titration.

108

109 **2.2. NDT measurements**

110 *Radar technique*

111 The radar techniques developed in the framework of this study relied on commercial
112 ground-penetrating radar (GPR) systems, using SIR-3000 systems from Geophysical
113 Survey Systems Inc. (GSSI®) and two separate ground-coupled 1.5 GHz antennas. Two
114 approaches were employed. One of them used four offsets (transmitter-receiver
115 distance), ranging from 7 to 14 cm, with an absorbing sponge placed between the
116 transmitter and the receiver, in order to measure the direct wave in the medium without
117 distortion due to the direct air wave [16]. Few observables were studied with this

118 configuration: the velocity, the corresponding relative permittivity and the attenuation
119 from the direct wave, and the arrival time for the largest offset. For the attenuation, the
120 observable studied corresponded to the slope coefficient of the logarithm of the
121 amplitudes.

122 The second approach, with one standard 1.5 GHz antenna, directly measured the peak-
123 to-peak amplitude of the direct wave in the medium [6-7]. This amplitude was
124 normalized to the peak-to-peak amplitude of the signal in air. For both configurations,
125 the coupled thickness of the medium, in the near vicinity of a GPR antenna which
126 interacts with it, can be estimated at 8-10 cm.

127

128 *Capacitive technique*

129 This technique, and the corresponding sensor, was designed by the network of
130 laboratories of the Ministry of Ecology, Sustainable Development and Energy (France)
131 and tested in reinforced concrete structures [16-18]. The principle of the capacitive
132 technique is to measure the resonance frequency of an oscillating circuit (around 30-35
133 MHz) between several electrodes lying on the upper face of the concrete slab. A
134 calibration allows the concrete relative permittivity ϵ'_r to be obtained, which is mainly
135 related to the water content and the mixture components. The volume investigated
136 depends on the geometry of the electrodes (coupled depth of roughly 1-2 cm for
137 medium sized electrodes – ME – and 6-8 cm for large electrodes – GE).

138

139 *Resistivity technique*

140 The technique tested in this study used a four-probe square device that injects electrical
141 current between two lateral probes and measures the potential difference between the

142 other two probes [18-20]. The apparent resistivity is deduced from the ratio of the
143 potential to the intensity, according to the geometrical characteristics. Measurements,
144 with two spacings (5 and 10 cm), were performed for two orthogonal directions of
145 electrical current injection and then averaged, for coupling thicknesses of about 3 and 6
146 cm respectively. For an accurate analysis, given the wide range of variation of resistivity
147 between concretes in different states of moisture and chloride content, it is necessary to
148 study the resistivity in its logarithmic form (Log(Res)).

149 In the following text, the term “observable” will be used as a generic term for all the ND
150 studied observables (Table A2, in appendix).

151

152 3. Laboratory results

153 The first campaigns in the SENSO project showed that most of the NDT techniques
154 tended to give results that varied linearly with the indicators. As the EM techniques are
155 sensitive to both water and chloride content, and indirectly to the porosity, some
156 regression functions to one indicator can only be proposed when the other two are
157 constant. The data were processed to fit a multi-linear regression (3-parameter) function
158 on the three indicators, under the hypothesis of averaged values without depth gradient.
159 Equation 1, for the GPR velocity, is presented as a model equation:

$$160 \quad \text{Velocity}_{GPR} = a \cdot \text{Poro} + b \cdot S_r + c \cdot \text{Cl}^- + d \quad (1)$$

161 where *Poro*, *S_r* and *Cl* correspond to the porosity, the saturation rate and the chloride
162 content, respectively, and *a*, *b*, *c* and *d* to the multi-linear regression coefficients.

163 Some ND observables require specific adaptation, such as the GPR signal attenuation
164 and the resistivity measurements. Concerning the electrical resistivity, for concrete, as
165 for porous materials, the empirical Archie’s law is used and expressed as:

166
$$R = a \cdot Poro^{-m} \cdot R_w \cdot S_r^{-n} \quad (2)$$

167 where the porosity, $Poro$, and the saturation, S_r , are clearly factors influencing the
168 resistivity R , and where the influence of chloride is represented through the interstitial
169 fluid resistivity (R_w). Expressed in logarithmic terms, the law becomes:

170
$$\text{Log } R = \text{Log } a - m \cdot \text{Log } Poro + \text{Log } R_w - n \cdot \text{Log } S_r \quad (3)$$

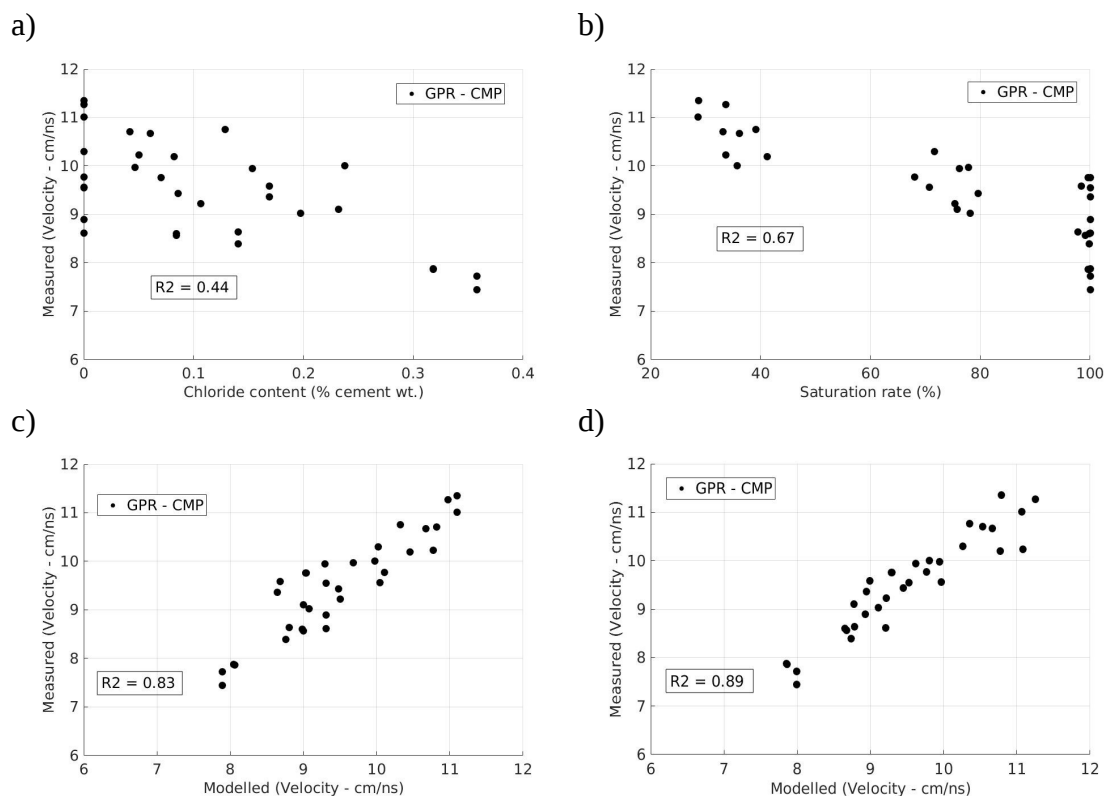
171 where, considering the range of variation for porosity (12 to 18%) and saturation (40 to
172 100%), we can accept that $\text{Log } Poro$ and $\text{Log } S_r$ are proportional to $Poro$ and S_r ,
173 respectively. For Cl , a link with R_w also exists [21-22]. Finally, the linear regression
174 approach chosen (Eq. 1), is very comparable with the well known Archie's law for
175 resistivity; and a , b , c and d are indicators of a , m , and n of the Archie's law. Similarly,
176 as the GPR attenuation is exponential through its propagation in a medium, a
177 logarithmic approach enables the model equation shown in Eq. 1 to be used.

178 Figure 1 presents, through the example of the GPR velocity, the dispersion of the
179 measurements when only one indicator is considered (Fig.1a-b), or when two or the
180 three indicators are considered through the modelling of the velocity using the multi-
181 linear regression coefficients from Equation 1 in Figures 1c-d. We note that the
182 determination coefficient R^2 is not significant (< 0.7) for the simple regressions (Figs
183 1a-1b) but it increases notably to 0.83 for a 2-parameter regression on S_r and Cl
184 (Fig.1c), and rises to 0.89 for the last case (Fig. 1d), showing that it is necessary to take
185 all of these three indicators into account.

186 From a statistical point of view, the threshold chosen for a test of significance is defined
187 by the Student law, for 33 samples and a 97.5% confidence interval. This test, applied to
188 the chloride content coefficient, showed that the ratio of the coefficients, c , to their
189 standard-deviations σ_c , calculated by the multi-regression (3-parameters), had to remain

190 above the threshold 2.037.

191 With this approach for each ND method, the coefficients of the regression were assessed
192 as a function of porosity, saturation rate, and chloride content. For all the EM ND
193 techniques, values depended on the chloride contents assessed at different depths (5, 10,
194 15, 20 mm and average). Table 2 summarizes the values obtained in the test of
195 significance. The results confirm that all the EM ND techniques are sufficiently
196 sensitive and reliable as far as the estimation of the chloride content is concerned. We
197 note that the highest values (in bold in the table) are obtained when the depth of the
198 estimation of the chloride content tends to the coupled volume of the ND technique.



199 **Fig. 1.** GPR velocity measurements, obtained by CMP, as a function of a) the chloride content,
200 b) the saturation rate, c) the GPR velocity modelled using the 2-parameter regression (S_r and
201 Cl_t), d) the GPR velocity modelled using the 3-parameter regression (S_r , Cl_t , Por_o)

202 Table 3 shows the regression coefficients obtained by keeping the case (depth for
203 estimation of chloride content) leading to the best value in the test of significance, for

204 each technique.

205 The values of the coefficients of the indicators, corresponding to Equation 1 and
 206 presented in Table 3, enable the ND measurements to be linked to the modelled ones.
 207 Some examples of modelling (one per technique) are shown in Figure 2. Their
 208 coefficients of determination (R^2) vary from 0.67 for the GPR (Time Offset-L parameter
 209 observable) to 0.78 for the capacitive technique (LE), values which increase to above
 210 0.8 when removing one apparent outlier. These results show that, even if the chloride
 211 contents are not perfectly constant versus depth in the mixes, the multi-linear regression
 212 remains efficient to estimate Cl^- , while taking S_r and $Porosity$ into account.

213 **Table 2.** Values obtained in test of significance, applied to the Cl^- coefficient, for the ND techniques
 214 according to the chosen total chloride content (at 5, 10, 15 and 20 mm and average)

		Test of significance values (> 2.037)				
	Technique	Total chloride at 5 mm	Total chloride at 10 mm	Total chloride at 15 mm	Total chloride at 20 mm	Total chloride average
Resistivity	Q5	5.25	5.04	5.03	5.33	5.34
	Q10	4.31	4.10	4.23	4.53	4.41
Capacitive	AE	5.75	5.85	5.47	5.43	5.85
	LE	6.22	6.31	6.08	6.38	6.51
GPR	Epsilon	3.50	4.44	5.24	5.66	4.64
	Velocity	3.66	4.47	4.99	5.28	4.59
	Log(peak-to-peak)	5.90	6.27	6.47	7.30	6.68
	Ampl CMP	3.83	4.55	5.17	5.67	4.80
	Ampl Offset-L	6.75	6.96	6.95	7.13	7.26
	Time Offset-L	3.15	3.24	3.35	3.59	3.39

215

216 It is interesting to note that Hugenschmidt and Loser [8] obtained very similar values,
 217 about 0.81 for the GPR attenuation (in logarithmic units), versus Cl^- , using air-coupled 2
 218 GHz echoes on concretes containing chlorides. These values are close to our coefficient
 219 of 0.77 for Cl^- for the GPR log (peak-to-peak) observable. Sbartai & al. [23] also found

220 similar results, with a value of about 0.74, for the coefficient related to Cl , using
 221 ground-coupled GPR antennas at 1.5 GHz and a normalized reflected echo (in
 222 logarithmic units), on homogeneous concrete slabs having 14-15 % porosity. This
 223 means that several distinct and independent studies have led to the same reliability for
 224 attenuation versus chloride content. This may be considered as a classical dependency.
 225 Nevertheless, there is no discussion of uncertainties in these papers.

226 **Table 3.** Coefficient of the multi-regressions of the ND techniques performed in their optimal
 227 configuration of chloride content (corresponding to the greatest a/σ_a)

		Coefficients						
		Coef. a for	Coef. b for	Coef. c for	Coef. d	R ²	Chloride	
Techniques		Poro	S _r	Cl			content	
Resistivity	Q5	-0.167	-0.0083	-3.574	5.993	0.76	Average	
	Q10	-0.157	-0.0079	-3.383	5.637	0.73	20 mm	
Capacitive	AE	1.037	0.0739	33.30	-8.559	0.72	10 mm	
	LE	0.612	0.0757	28.92	-3.527	0.78	Average	
GPR	Epsilon	0.246	0.0519	9.628	1.600	0.85	20 mm	
	Velocity	-0.105	-0.026	-3.397	13.45	0.89	20 mm	
	Log(peak-to-	-0.0125	-0.0007	-0.763	-0.077	0.77	20 mm	
	peak)							
	Ampl CMP	-0.0015	-0.0003	-0.105	-0.0189	0.73	20 mm	
	Ampl Off.-L	-0.0070	-0.0009	-0.227	0.308	0.87	Average	
	Time Off.-L	0.0181	0.00235	0.5245	0.788	0.67	20 mm	

228

229 The influence of chlorides on electrical resistivity is complex since the interstitial fluids
 230 in concrete are naturally conductive. Fluid in concrete depends on the composition of
 231 the cement and additions, so it is influenced by alkali content: the more alkali there is in
 232 the pore water, the smaller is the influence of external fluid [21]. The real value for R_w
 233 in the Archie's law is a composition of conductance of fluids from the concrete and
 234 from external ingresses [24]. Numerous works present the relationship between

235 electrical resistivity and chloride diffusivity [25-27]. The Nernst-Einstein relationship,
236 used to describe chloride ingress in concrete structure, could be simplified by taking the
237 ideal hypothesis of a constant value for the ion diffusivity, which would give:

$$238 \quad c_i = k \cdot \left(\frac{1}{R}\right) \quad (4)$$

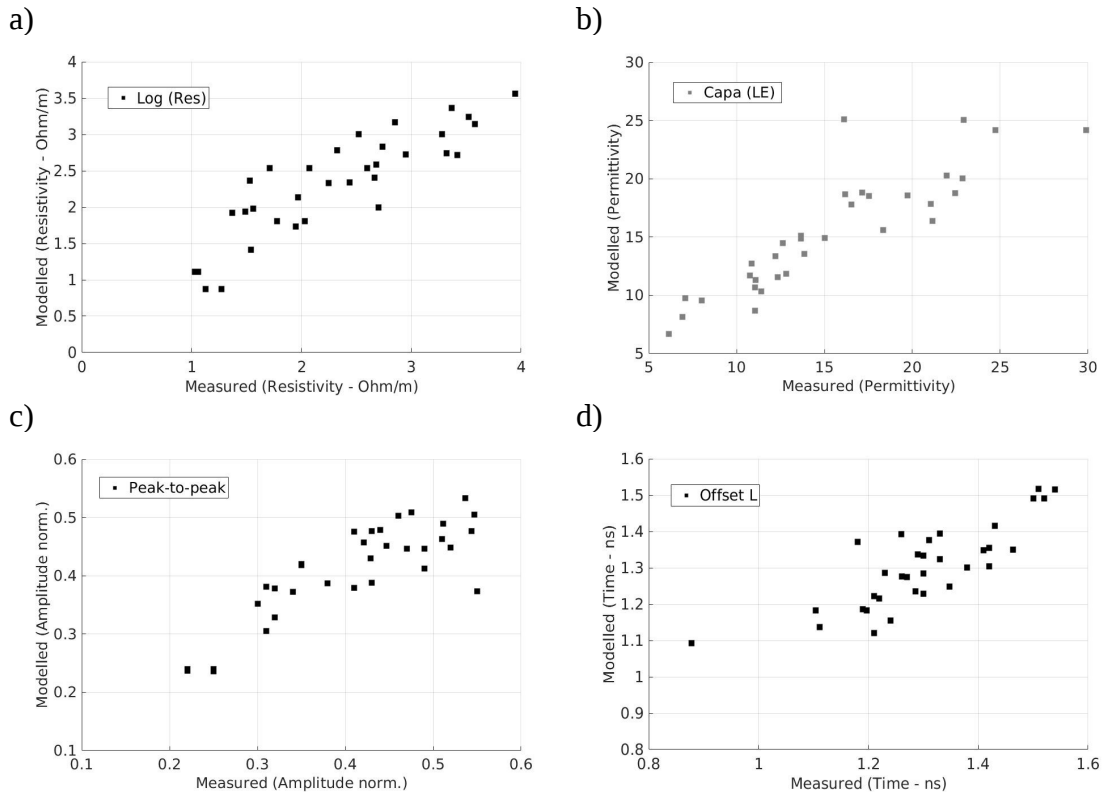
239 with c_i the concentration of ion i in the pore water; k a constant deduced from the
240 Nernst-Einstein relationship and associated with the gas constant, the absolute
241 temperature, the ionic valence, the Faraday constant, the ion transport number, and its
242 activity coefficient; and R the electrical resistivity. Apart from ideal cases, the
243 complexity of interactions between concrete interstitial fluid and chlorides may explain
244 why there is no report on the electrical resistivity of concrete versus chloride content of
245 pore water.

246 To avoid any influence of the ranges of variation for indicators and measurement on the
247 coefficients of the laws, a supplementary step was performed in this study through the
248 normalization (from 0 to 1) of the ND measurements and the indicator values, in the
249 range of their respective values. This allows the techniques and the coefficients to be
250 compared amongst themselves. Concerning the three indicators, their ranges are the
251 following: [0-~0.36% of dry concrete mass] for Cl , [28-100%] for S_r and [12.5-18.1%]
252 for $Poro$.

253 In Table 4, while focusing on the indicators, the chloride content coefficient presents the
254 highest values for all the EM techniques, except for the “Time Offset-Large”
255 observable. The ND approaches, focused on the attenuation of the radar wave, the
256 capacitive and the resistivity techniques, remain the most sensitive to chloride content,
257 the “GPR log (peak-to-peak)” observable being twice as sensitive as the others.

258 Concerning the saturation rate, the ND techniques devoted to time or velocity of radar

259 wave propagation are the most sensitive, slightly more than for the chloride content.
 260 The difference between the capacitive technique and the GPR time or velocity can be
 261 explained by the fact that the EM characteristics of civil engineering materials at the
 262 frequencies used (very low GPR frequency band) are sensitive to both chloride and
 263 water content [28], due to the predominant effect of interfacial polarization.



264 **Fig. 2.** Comparison of the measured and calculated observables for a) the resistivity technique
 265 – quadripole 5 cm b) the capacitive technique – large electrodes, c) the GPR Log(peak-to-peak)
 266 amplitude, d) the GPR amplitude (large offset), at their optimal configuration

268 **Table 4.** Coefficient of the multi-regressions of the ND normalized measurements performed in their
 269 optimal configuration of chloride content (corresponding to the greatest a/σ_a)

Coefficients obtained with normalized observables and indicators	
Techniques	Coef. <i>a</i> for Poro Coef. <i>b</i> for S_r Coef. <i>c</i> for Cl^- Chloride content

Resistivity	Q5	-0.32	-0.20	-0.45	Average
	Q10	-0.35	-0.23	-0.48	20 mm
Capacitive	AE	0.18	0.17	0.38	10 mm
	LE	0.14	0.23	0.45	Average
GPR	Epsilon	0.15	0.4	0.37	20 mm
	Velocity	-0.15	-0.48	-0.31	20 mm
	Log(peak-to-peak) Ampl CMP	-0.18	-0.12	-0.69	20 mm
	Ampl Off.-L	-0.11	-0.25	-0.49	20 mm
	Time Off.-L	-0.23	-0.39	-0.49	Average
	Time Off.-L	-0.20	-0.39	0.28	20 mm

270

271 Finally, for the porosity estimation, the electrical techniques give the best performance.
 272 This can be explained by the increase in connectivity of pores as the porosity increases,
 273 which facilitates ionic displacement and thus the electric current, especially for
 274 saturation degrees higher than 40%.

275 This normalized study thus shows that all these EM techniques are capable of providing
 276 information on the following indicators: chloride content, saturation rate and porosity, in
 277 concrete mixes. Their sensitivity to these indicators encourages complementary use of
 278 these ND techniques if we want to dissociate the indicators surveyed.

279

280 **4. On-site implementation and discussion**

281 The objective of the campaign described here is to estimate the uncertainty on the
 282 values of indicators from ND measurements made at a real site in a tidal zone, using the
 283 regressions studied above and the corresponding uncertainties (from the ND
 284 measurement and from the regression). Given their high sensitivity to chlorides, three
 285 techniques were considered for comparison, out of the three NDT families: resistivity,
 286 capacity and GPR. By performing statistical calculations, this study, described below,
 287 will quantify the influence of the ND measurements or the regressions on indicator

288 estimation, from a structural engineering point of view. As the calibration was not
 289 performed on the structure in question, only the uncertainties will be studied, and not
 290 the absolute values, for which no reliability estimate can be made.

291 **4.1. Presentation of the site**

292 The chosen test site was a 15-year-old reinforced concrete wharf at the port of Saint-
 293 Nazaire (France). A large ND campaign was carried out on the site in the framework of
 294 the SENSO project, in which all the authors participated. The wharf, the ND techniques,
 295 and the destructive analysis are accurately described in [15] and EM values in [29].

296 The structure tested was a precast reinforced concrete beam exposed to chloride ingress
 297 in a tidal zone. The concrete mix used a CEM II/A 32.5PM cement with a water-to-
 298 cement ratio of 0.46, and included fly ash and siliceous aggregates as components. The
 299 standard tests showed a 28-day compressive strength of about 36 MPa. Gas
 300 permeability measurements on five cores gave values corresponding to a porosity in the
 301 11-12% range, and chloride profiles were also obtained from these cores.

302 The chloride profiles, presented in [15], show values of total chlorides per weight of dry
 303 concrete of about 0.025% in the first 5 mm, a maximum of 0.09+/-0.01% at 15+/-2 mm
 304 and then a linear decrease to 0.03% at about 32 mm.

305

306 **Table 5.** *ND measurements performed on a concrete wharf at Saint-Nazaire (FR): averaged values and*
 307 *standard deviation per line between brackets*

		Res Q5	Capa LE	GPR velocity	GPR Ampl off L
Internal side	Line 1	3.52 (0.399)	5.97 (0.374)	11.53 (0.163)	0.51 (0.0316)
	Line 2	3.41 (0.366)	6.21 (0.384)	11.46 (0.217)	0.51 (0.0263)
	Line 3	3.35 (0.283)	6.25 (0.369)	11.47 (0.224)	0.50 (0.0218)
External side	Line 1	3.36 (0.323)	6.91 (0.133)	11.05 (0.282)	0.45 (0.0182)
	Line 2	3.41 (0.365)	6.95 (0.254)	10.94 (0.271)	0.44 (0.0286)
	Line 3	3.45 (0.431)	6.94 (0.189)	11.04 (0.246)	0.45 (0.0203)

NDT method	S.D	0.012	0.0003	0.003	0.0055
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308

309 ND measurements were performed on each side of the beam – the external side exposed
 310 to wind, rain and ocean spray, and the protected, internal side under the wharf deck – on
 311 three horizontal lines. Thirty measurements were recorded per face, at the centre of the
 312 reinforcement meshes. The ND values shown in Table 5 are the average of each line. An
 313 ND procedure repeated several times at one point (centre of a reinforced mesh) in order
 314 to find the standard deviation (S.D.) of each NDT method on the structure (last line of
 315 table 5).

316

317 **4.2. Methodological approach**

318 Non-destructive measurements led to the determination of the observables, from which
 319 the indicators were deduced through the inverse analysis of a specific relationship for
 320 each technique, for instance Eq.1. During this process, uncertainty appeared at various
 321 levels, mainly (Table 6 based on Eq.1):

- 322 • on the measurement (uncertainty on observable). This uncertainty was assessed
 323 during the investigation of the structure by repeated measurements. For this
 324 study, the measurement uncertainty is the standard deviation of repeated
 325 measurements relative to the average value (in other words the Coefficient of
 326 Variation CoV), given in terms of relative uncertainty;
- 327 • on the relationship between observable and indicator (model error). This error is
 328 linked to the reliability of the calibration process. In this study, it corresponds to
 329 the standard error value of the parameter considered, as assessed during the
 330 linear regression calculation relative to the average value of the parameter (the
 331 CoV).

332 The sensitivity analysis showing the effect of these various uncertainty levels on
 333 diagnostic reliability is performed through a Monte Carlo simulation. It consists of
 334 performing repeated sampling for a parameter described by its statistics (average and
 335 CoV). The simulated population respects the same statistical distribution. Then from
 336 each “simulated uncertain term” of the population, it is possible assess the uncertainty
 337 propagating to the final result. For this study, and at each step, 1000 values were
 338 simulated. According to the objective, the uncertainties could be simulated on different
 339 parameters.

340 **Table 6.** *Uncertainty levels on Eq.1*

parameter	for instance in Eq.1	Symbol	uncertainty	uncertainty level
Observable	Velocity GPR	V_{GPR}	$\pm \delta V_{GPR}$	measurement
law	Porosity coefficient	a	$\pm \delta a$	calibration
law	Saturation coefficient	b	$\pm \delta b$	calibration
law	Chloride content coefficient	c	$\pm \delta c$	calibration
law	Constant coefficient	d	$\pm \delta d$	calibration
indicator	Porosity	$Poro$	$\pm \delta Poro$	interpretation
indicator	Saturation rate	Sr	$\pm \delta Sr$	interpretation
indicator	Chloride content	Cl	$\pm \delta Cl$	interpretation

341

342 If the measurement uncertainty is considered, with the perfect regression model, δV_{GPR}
 343 exists, and δa , δb , δc , δd are equal to 0. Respectively one thousand “measured” values
 344 are considered (statistically correct), leading to the calculation of a thousand values for
 345 $Poro$, Sr and Cl after inversion. Thus the average values can be assessed for each
 346 indicator as well as $\delta Poro$, δSr , and δCl . If the measurement is considered as perfect
 347 and the uncertainty is only on the regression model, δV_{GPR} equals 0, and δa , δb , δc , δd
 348 exist. From measurements, and considering the thousand values each for a, b, c and d
 349 (for the observable under consideration) to be statistically correct, a thousand values for

350 poro, S_r and Cl are assessed by inversion. Here again, average values are assessed for
 351 indicators and for $\delta Poro$, δS_r , and δCl . Then, both approaches are studied and the
 352 uncertainties on $Poro$, S_r and Cl are compared.

353 Moreover, the inversion process is carried out considering matrix calculations (Eqs 5 to
 354 7) with O the matrix of observables, d the matrix containing the constant term of each
 355 regression, I the matrix of indicators, and M the matrix of regression coefficients.
 356 Inversion consists to of determining the matrix $[M]^{-1}$, inverse of $[M]$, thus leading to the
 357 assessment of its determinant: $\text{Det}(M)$.

$$358 \quad [O] - [d] = [I] \times [M] \quad (5)$$

359 with

$$360 \quad \begin{bmatrix} obs1 \\ obs2 \\ obs3 \end{bmatrix} - \begin{bmatrix} d1 \\ d2 \\ d3 \end{bmatrix} = \begin{bmatrix} indic1 \\ indic2 \\ indic3 \end{bmatrix} \cdot \begin{bmatrix} a1 & b1 & c1 \\ a2 & b2 & c2 \\ a3 & b3 & c3 \end{bmatrix} \quad (6)$$

361 Inversion consists of assessing $[M]^{-1}$ in order to solve the following equation:

$$362 \quad [I] = ([O] - [d]) \times [M]^{-1} \quad (7)$$

363 This problem is not solvable if $\text{Det}(M)$ is equal to 0, which would correspond to the
 364 situation where the models have the same coefficients of regression. In this case, no
 365 additional information would be provided by any NDT method compared with the
 366 others. If $\text{Det}(M)$ is very close to 0, the calculation error will be very high. To overcome
 367 this difficulty it is decided to consider uncertainties of indicators, namely $\delta Poro$, δS_r ,
 368 and δCl instead of the indicators themselves.

369

370 **4.3. Influence of types of uncertainty of NDT methods**

371 For this study, we considered the triplet: resistivity Q5, capa LE, and GPR velocity,

372 chosen as the three techniques presenting the best relationship to chloride content in
 373 each of the three NDT families (see R² values in Table 3).

374 An overview of the results is given in the following tables (7, 8 and 9). Case 1
 375 corresponds to ND values associated with their average standard deviation per line,
 376 which includes a part of the material variability along the beam. Case 2 corresponds to
 377 the standard deviation calculated at a measurement point, which corresponds to the
 378 technique variability. Standard deviations decrease from roughly 40, 28, 23 and 2.4% in
 379 case 1 to 1.2, 0.03, 0.3 and 0.55% in case 2 for res_Q5, capa_LE, GPR velocity and
 380 GPR_Ampl_off_L, respectively.

381 The first observations in Tables 7 and 8 show that uncertainties on the regression
 382 models lead to an unacceptable estimation of indicators. The models obtained from
 383 laboratory experiments, which were not suited to Saint Nazaire wharf, are used. This is
 384 made obvious by the negative values for chloride factors. So, the influence of model
 385 error or measurement uncertainty is estimated by the error of indicator assessment and
 386 not to by the value of the indicator. This implies that a calibration of the regression
 387 models is necessary for each ND technique for every ND inspection on a new concrete
 388 structure.

389

390 **Table 7.** Statistical inversions of the ND measurements, performed on a concrete wharf (Table 5), under
 391 the hypothesis of perfect regression models or perfect measurements and considering Case 1

Case 1	Perfect models (uncert. on meas.)			Perfect measurements (uncert. on models)		
	Porosity	Sat	Cl-	Porosity	Sat	Cl-
L1	14.3 (29%)	19.1 (65.3%)	-0.025(306%)	19.2 (447%)	20.3 (768%)	-0.17 (1569%)
Int. side L2	15.2 (26.2%)	19.7 (76.1%)	-0.036 (217%)	20.4 (447%)	21.2 (773%)	-0.19 (1460%)
L3	15.9 (19.1%)	18.1 (79.2%)	-0.046 (143%)	21.2 (94.4%)	19.1 (882%)	-0.21 (1426%)
Ext. side L1	15.2 (24.1%)	17.4 (46%)	-0.060 (127%)	20.2 (433%)	42.2 (388%)	-0.22 (1257%)
L2	14.7 (27.2%)	17.4 (37.6%)	-0.070 (114%)	19.5 (429%)	50.0 (321%)	-0.22 (1198%)

L3	14.0 (33.3%)	16.8 (40.4%)	0.044 (198%)	18.7 (433%)	44.5 (349%)	-0.19 (1351%)
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392

393 As inversions show similar results for the internal and the external sides, only the values
394 of the internal face are presented below.

395

396 **Table 8.** *Statistical inversions of the ND measurements, performed on the internal side of the*
397 *concrete wharf (Table 5), under the hypothesis of perfect regression models or perfect*
398 *measurements and considering Case 2*

Internal side	Perfect models (uncert. on meas.)			Perfect measurements (uncert. on models)		
	Porosity	Sat	CI-	Porosity	Sat	CI-
L1	14.4 (0.9%)	18.6 (1.6%)	-0.026 (8.3%)	19.2 (447%)	20.3 (768%)	-0.17 (1569%)
Case 2 L2	15.3 (0.8%)	19.4 (1.6%)	-0.038 (5.5%)	20.4 (447%)	21.2 (773%)	-0.19 (1460%)
L3	15.9 (0.8%)	17.4 (1.7%)	-0.044 (4.7%)	21.2 (94.4%)	19.1 (882%)	-0.21 (1426%)

399

400 The analysis of Table 7 is mainly focused on the uncertainty values (percentage in bold
401 characters in brackets), and not on the values themselves, since the regression models
402 are not created on the surveyed concrete but on laboratory slabs. The first findings show
403 extremely high levels for $\delta Poro$, δSr , and δCI^- in the case of uncertainty of models, in a
404 range ten times above those for the case of uncertainty of measurements.

405 The second point concerns the comparison of cases 1 and 2 when considering perfect
406 models. We can note similar values of indicators but a large difference in the uncertainty
407 values. Taking account of the variability of ND measurements from a large zone (Case
408 1) on the inversion induces results that are unacceptable because unreliable. We must
409 consider only the uncertainty of the NDT on this concrete mix (obtained from the
410 repetitive procedure on one representative local zone) rather than the integrated
411 uncertainty combining NDT and the variability of the material.

412 Finally, from a structural engineering point of view, the uncertainties on the indicators

413 *Poro*, *Sr*, and *Cl* give rise to acceptable ranges when the hypothesis of perfect
 414 regression models is maintained (if they can be designed on the concrete being
 415 surveyed) and when the standard deviation of each ND technique is found on site.

416

417 **4.4. Influence of combination of observables**

418 The choice of the three techniques also has an influence on uncertainties of assessment.
 419 We compare the results obtained when the techniques were selected on their own
 420 reliability with respect to chloride variations (as in Section 3, techniques chosen on the
 421 R^2 value, see Table 3), or if the techniques were chosen according to their
 422 complementarity (based on the assessment of the highest determinant value, see Eqs. 5
 423 to 7).

424 The two cases are studied in Table 9, which shows the influence of observable
 425 combination on the assessment of indicators. As expected, when the value of $\text{Det}(M)$
 426 decreases too much, the inversion process induces unacceptable uncertainties, as seen
 427 for the triplet Techn. Res (Q5) / Capa (LE) / GPR ampl.

428

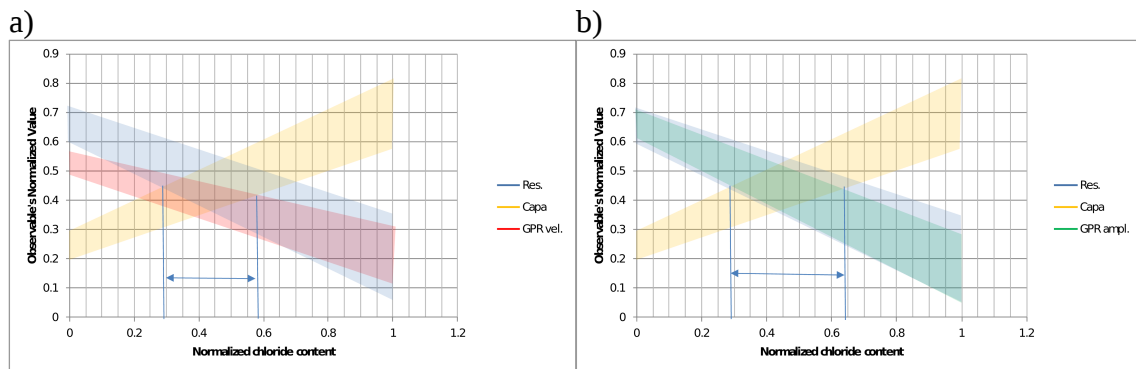
429 **Table 9.** Statistical inversions of the ND measurements, performed on the internal side of the
 430 concrete wharf (Table 5), including either the GPR velocity or the GPR amplitude

Perfect models (uncert. on meas.)		Porosity	Sat	Cl-
<i>Techn. Res / Capa / GPR vel.</i>	Line 1	14.4 (0.9%)	18.6 (1.6%)	-0.026 (8.3%)
Average S.D. per line	Line 2	15.3 (0.8%)	19.4 (1.6%)	-0.038 (5.5%)
Det = -0.0464	Line 3	15.9 (0.8%)	17.4 (1.7%)	-0.044 (4.7%)
<i>Techn. Res / Capa / GPR ampl.</i>	Line 1	4.7 (4.5%)	-849 (1.9%)	2.45 (1.8%)
Off. L	Line 2	4.2 (5.0%)	-965 (1.6%)	2.77 (1.6%)
Average S.D. per line	Line 3	3.0 (6.9%)	-1129 (5.9%)	3.23 (1.3%)
Det = -0.00092				

431

432 An explanation can be furnished by Figure 3, which shows the regression relations for
 433 the two distinct NDT triplets (from Table 9) while focusing on chloride. Ideally, the
 434 estimation of chloride content should be made by the intersection of the three
 435 regressions. In both cases, there is no single intersection of the three curves.
 436 Nevertheless, the uncertainty of the apparent solution (not exact since the calibration
 437 does not correspond to the material under study) is represented by the band covered by
 438 the three ranges of uncertainty for each of the observables.

439 The bandwidth of uncertainty on chloride content varies from less than 0.3 for the first
 440 case (blue arrow in Fig. 3a), to more than 0.35 for the second case (blue arrow in Fig.
 441 3b). The closer the three regressions intersect (the farther the determinant from Eq. 7
 442 from 0) the less uncertainty there is. Then, for the second case, it is shown that both
 443 resistivity and GPR amplitude have similar sensitivities to chloride (expressed by a
 444 determinant very close to 0), and the third technique does not significantly improve the
 445 assessment of indicator. For these two cases DET are -0.0464, and -0.0009, respectively.
 446



447 **Fig. 3.** Regressions of selected ND techniques (normalized values) versus chloride content for
 448 the triplets a) Techn. Res (Q5) / Capa (LE) / GPR velocity and b) Techn. Res (Q5) / Capa (LE) /
 449 GPR ampl. The bandwidths correspond to the uncertainties of each regression.

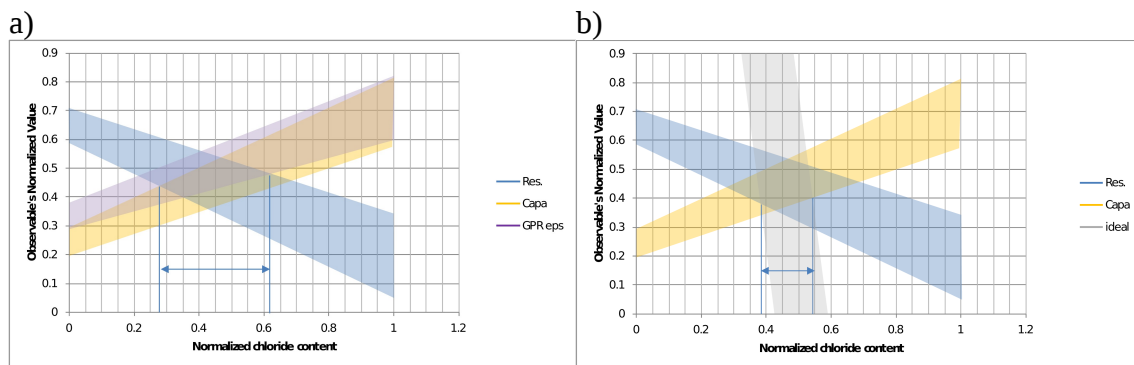
450

451 **4.5. Discussion on how to choose an ideal third ND technique**

452 The question of the choice of three complementary techniques could be then based on
 453 the determinant value. To test this approach, and having already chosen the resistivity
 454 and capacitive techniques, a third NDT is chosen: GPR epsilon, which leads to $\text{Det}(M)$
 455 $= 0.0721$. The estimation of chloride content uncertainty with this new triplet (Fig. 4a)
 456 is 0.35. This value is in the range of the first results, proving that this approach is not
 457 sufficient when working with EM techniques.

458 Going further in this study, we also tested this criterion by considering an ideal virtual
 459 technique fairly perpendicular to the first two (Fig. 4b). The uncertainty level of this
 460 technique was taken to be in the same range as the others. The result shows a chloride
 461 content uncertainty decreasing to 0.15. Finally, it should be noted that the uncertainty of
 462 the ideal ND technique could strongly influence the uncertainty on indicators, even if
 463 the intersection is quite perpendicular (that is to say, even if the determinant is high).

464



465 **Fig. 4.** Regressions of selected ND techniques (normalized values) versus chloride content for
 466 the triplets a) Techn. Res (Q5) / Capa (LE) / GPR eps and b) Techn. Res (Q5) / Capa (LE) /
 467 ideal techn. The bandwidths correspond to the uncertainties of each regression.

468

469 **5. Conclusion**

470 The results presented in this paper concern the implementation of different NDT
 471 methods (using radar, capacitive and resistivity techniques) for the detection of

472 chlorides in concrete. Three different concrete mixes were tested in the laboratory with
473 different levels of saturation and involving two concentrations of NaCl. A multi-linear
474 regression, depending on the three indicators: chloride content, saturation rate and
475 porosity, was performed for each ND technique, under the hypothesis of averaged
476 indicator values without a depth gradient.

477 The results show that all the techniques devoted to attenuation measurements or the
478 resistivity are very sensitive to the presence of chlorides. This phenomenon is less
479 visible for the relative permittivity, as the frequency increases in the GPR frequency
480 band. Concerning the other two indicators, more than half of the ND techniques are less
481 than half as sensitive to them as to the chloride content.

482 Experiments on a real site in a marine environment have shown that it is necessary to
483 take two other indicators into account: the saturation rate and the porosity, to properly
484 estimate the chloride content through a multi-linear regression approach. A statistical
485 study was performed on the influence of the accuracy of ND measurements and the
486 model error on chloride content, from a structural engineering point of view.

487 The principal results show that:

- 488 - all the ND techniques must be calibrated on the structure actually surveyed,
- 489 - the combination of 3 techniques sensitive to chloride is not necessarily the best ND
490 triplet,
- 491 - the determinant of the regression equations considered as an indicator of reliability
492 (for chloride estimation), is not sufficient because it is sensitive to the 3 techniques,
- 493 - when considering a virtual ideal technique (the regression slope of which would be
494 “perpendicular” to those of the other techniques), the parametric study shows the
495 importance of the uncertainty of each technique in the estimation of the chloride

496 content.

497 Finally, it is illusory to believe that it is possible to accurately estimate the chloride
498 content of a concrete structure using the hypothesis that all other indicators are spatially
499 constant. The paper has highlighted the present limitations of the various possible
500 approaches for chloride content assessment.

501

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508

509 **Glossary**

510 Chloride content: ratio (percentage) of the weight of total chloride (free and bound) to
511 the weight of dry concrete.

512 Durability indicator: property describing the concrete in term of durability and
513 performances (i.e. porosity, density, resistance, Young modulus, chloride content,
514 moisture...).

515 Indicator: generic term designating all durability indicators and more generally all the
516 properties involved in concrete durability

517 Multi-linear regression: approach of modeling the relationship between a dependent
518 variable (i.e. permittivity) and few conditioning variables (i.e. chloride content,
519 porosity...) using linear mathematical expression.

520 ND observable: direct value (i.e. permittivity, resistivity...) or extracted value (i.e. wave
521 attenuation or velocity...) from non-destructive (ND) measurements.

522 Porosity: ratio (in percentage) of the volume of void to the total volume of material.

523 Saturation rate: ratio (in percentage) of a volume of fluid (interstitial solution for
524 concrete) to the total volume of voids inside concrete.

525 uncertainty: statistical expression of the dispersion of a result, associated to the
526 imperfect and/or unknown information. For an inverse process to predict a value (ie.
527 Chloride content), it can result from both imperfect measurement and imperfect model.

528 Variability: expression characterizing the effect of the natural unmastered variations of
529 the material properties at the measurement scale. It leads to the dispersion of the
530 measurement results which can be attributed to the object (material) being measured.

531

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617

618 **Appendix**

619 **Table A1.** Saturation rate, porosity and total chloride content (by weight of dry concrete) for all
 620 *the concretes*

Sample	N°	Expected Sat. Rate	Porosity (%)	Sat. rate (%)	Total chloride at 5 mm	Total chloride at 10 mm	Total chloride at 15 mm	Total chloride at 20 mm	Total chloride average
G8	1		18.1	28.8	0.00	0.00	0.00	0.00	0.00
	2	40	18.1	33.1	0.08	0.07	0.06	0.04	0.06
	3		18.1	35.7	0.34	0.31	0.25	0.24	0.29
	4		18.1	68.1	0.00	0.00	0.00	0.00	0.00
	5	80	18.1	75.4	0.11	0.11	0.11	0.11	0.11
	6		18.1	75.8	0.26	0.22	0.21	0.23	0.23
	7		18.1	100.0	0.00	0.00	0.00	0.00	0.00
	8	100	18.1	99.1	0.14	0.08	0.07	0.08	0.10
	9		18.1	99.8	0.14	0.08	0.07	0.08	0.10
	10		18.1	99.6	0.39	0.34	0.34	0.32	0.34
	11		18.1	100.0	0.39	0.34	0.34	0.32	0.34
G3	12		15.5	28.7	0.00	0.00	0.00	0.00	0.00
	13	40	15.5	36.2	0.05	0.06	0.06	0.06	0.06
	14		15.5	39.1	0.19	0.16	0.14	0.13	0.15
	15		15.5	70.7	0.00	0.00	0.00	0.00	0.00
	16	80	15.5	79.6	0.24	0.10	0.06	0.09	0.12
	17		15.5	78.1	0.46	0.27	0.23	0.20	0.29
	18		15.5	100.0	0.00	0.00	0.00	0.00	0.00
	19	100	15.5	97.8	0.21	0.20	0.18	0.14	0.18
	20		15.5	99.8	0.21	0.20	0.18	0.14	0.18
	21		15.5	100.0	0.42	0.35	0.35	0.36	0.37
	22		15.5	100.0	0.42	0.35	0.35	0.36	0.37
G1	23		12.5	33.6	0.00	0.00	0.00	0.00	0.00
	24	40	12.5	33.7	0.10	0.07	0.06	0.05	0.07
	25		12.5	41.2	0.16	0.14	0.09	0.08	0.12
	26		12.5	71.7	0.00	0.00	0.00	0.00	0.00
	27	80	12.5	77.8	0.06	0.06	0.05	0.05	0.05
	28		12.5	76.2	0.18	0.13	0.17	0.15	0.16
	29		12.5	100.0	0.00	0.00	0.00	0.00	0.00
	30	100	12.5	100.0	0.17	0.12	0.08	0.07	0.11
	32		12.5	99.6	0.17	0.12	0.08	0.07	0.11
	32		12.5	100.0	0.37	0.25	0.19	0.17	0.25
	33		12.5	98.4	0.37	0.25	0.19	0.17	0.25

621

622

623

Table A2. ND measurements

Sample	N°	Capa (LE) (-)	Capa (ME) (-)	Log (Res - 5 cm) (Ω .m)	Log (Res - 10 cm) (Ω .m)	GPR velocity (cm/ns)	GPR pic- pic (-)	Log(GPR att.) (-)	GPR Ampl (D4) - (-)	GPR OD (D4) (ns)
G8	1	7.07	7.34	3.32	2.97	11.35	0.543	-0.054	0.154	1.104
	2	12.82	16.34	2.60	2.73	10.71	0.520	-0.055	0.165	1.220
	3	17.53	22.64	1.95	1.94	10.00	0.320	-0.066	0.100	1.330
	4	10.84	12.31	2.67	2.35	9.77	0.447	-0.063	0.115	1.261
	5	21.14	24.11	1.37	1.36	9.23	0.310	-0.077	0.071	1.410
	6	22.86	25.36	1.54	1.56	9.11	0.310	-0.095	0.045	1.430
	7	13.67	15.50	1.97	1.80	8.89	0.429	-0.065	0.104	1.463
	8	16.53	19.44	2.03	2.10	8.57	0.410	-0.084	0.052	1.260
	9	21.05	23.44	1.78	1.78	8.60	0.320	-0.084	0.049	1.330
	10	22.93	37.65	1.13	1.16	7.87	0.220	-0.088	0.028	1.540
	11	16.12	17.26	1.27	1.17	7.88	0.250	-0.105	0.023	1.510
G3	12	6.92	7.52	3.58	3.25	11.01	0.547	-0.058	0.181	1.112
	13	11.39	13.15	2.74	2.83	10.67	0.510	-0.053	0.155	1.190
	14	12.20	16.08	1.71	1.72	10.76	0.350	-0.052	0.166	1.300
	15	11.08	12.58	2.32	2.04	9.56	0.430	-0.071	0.142	1.285
	16	18.34	21.68	1.53	1.52	9.43	0.350	-0.073	0.082	1.380
	17	21.95	23.29	1.49	1.35	9.03	0.300	-0.080	0.056	1.420
	18	13.85	16.19	2.07	1.84	8.61	0.421	0.061	0.120	1.420
	19	19.72	19.71	2.70	2.74	8.64	0.550	-0.101	0.041	1.180
	20	22.43	24.34	1.56	1.57	8.39	0.340	-0.092	0.040	1.310
	21	29.90	27.76	1.03	1.03	7.45	0.220	-0.125	0.012	1.520
	22	24.74	23.17	1.06	1.02	7.72	0.250	-0.121	0.017	1.500
G1	23	6.15	5.86	3.94	3.38	11.27	0.537	-0.064	0.158	0.878
	24	11.04	12.38	3.37	3.50	10.23	0.460	-0.060	0.129	1.210
	25	11.04	13.52	2.85	2.82	10.20	0.440	-0.049	0.155	1.240
	26	8.02	7.59	3.52	3.22	10.30	0.475	-0.066	0.166	1.196
	27	12.35	12.96	2.52	2.51	9.97	0.410	-0.059	0.129	1.210
	28	12.62	14.09	2.68	2.64	9.95	0.490	-0.060	0.126	1.270
	29	10.75	11.17	3.28	3.06	9.55	0.511	-0.057	0.155	1.347
	30	15.02	15.85	3.42	3.52	9.76	0.490	-0.067	0.115	1.230
	32	13.65	15.40	2.95	3.01	9.76	0.470	-0.067	0.115	1.300
	32	17.14	17.75	2.25	2.27	9.36	0.380	-0.071	0.079	1.290
	33	16.19	18.62	2.44	2.41	9.58	0.430	-0.070	0.096	1.300

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