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Combination of the Wenner resistivimeter and Torrent permeameter methods for assessing carbonation depth and saturation level of concrete

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33 built for the relationships between resistivity or permeability and saturation degree and
34 carbonated depth. For resistivity, either a linear model between resistivity and saturation
35 degree is used or Archie's law is adapted to take the effect of carbonation into account.
36 Following the same idea, a linear law between Torrent permeability and saturation degree is
37 adapted to the effect of carbonation. Because resistivity can be measured only if the saturation
38 degree is rather high, i.e. if there is a continuity of the interstitial solution, and because
39 permeability assessment is impossible if the concrete is fully saturated, these laws are limited
40 to saturation degrees in the 40 to 83% range.

41 Then, these laws are used to predict carbonation depth and saturation degree on a wall
42 designed with the same concrete but stored in different conditions. The results show that
43 resistivity and Torrent permeability can be used for the combined assessment of carbonation
44 depth and saturation degree in laboratory conditions.

45 Keywords: Concrete, carbonation depth, saturation level, Torrent permeability, Wenner
46 resistivity

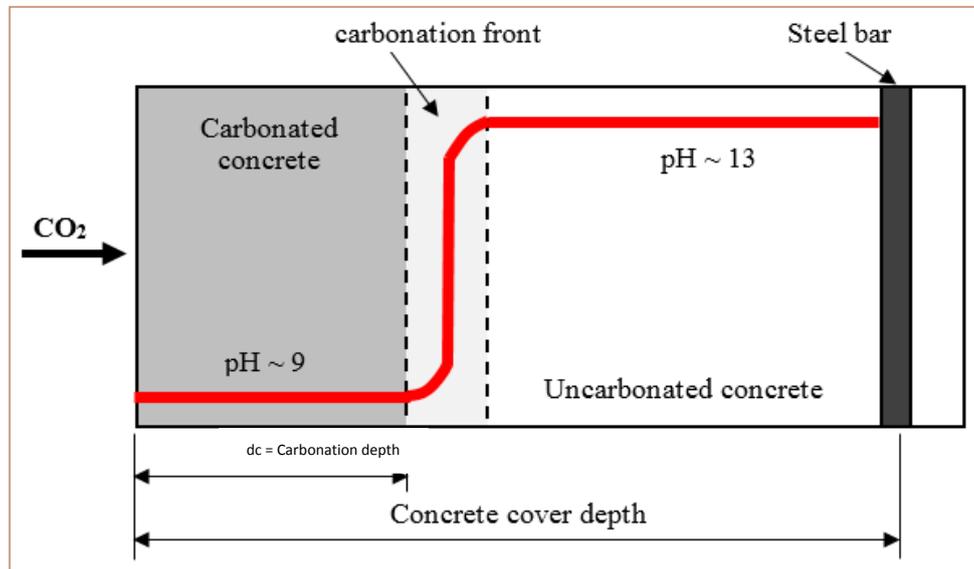
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48 1 Introduction

49 The corrosion of reinforcing steel within reinforced concrete structures produces damage such
50 as spalling of the concrete cover. Steel parts then remain uncovered and cause a sharp
51 decrease in the load-bearing capacity of the structure. This failure condition is usually due to
52 the presence of chloride or to a carbonation process. The present study was conducted to
53 examine, more specifically, the carbonation process. Carbonation is a physical-chemical
54 process, which may cause a decrease in concrete pH value from 13 to 9. Carbon dioxide from
55 the air (CO_2) reacts with the portlandite of concrete ($\text{Ca}(\text{OH})_2$) to form calcium carbonate
56 ($\text{CaCO}_3 + \text{H}_2\text{O}$) (Figure 1). If the whole of the concrete cover is carbonated, steel frame de-

57 passivation is initiated and results in the delamination of the concrete cover due to swelling of
58 the corroded steel.

59



60

61 *Figure 1: pH decrease in concrete cover due to carbonation [Ta 2016]*

62 According to a literature review conducted by Ta *et al.* [Ta 2016 and 2018], a considerable
63 amount of effort has been devoted to the study of the propagation of CO_2 and to the
64 examination of the factors affecting the carbonation rate, such as mix proportions in concrete
65 (e.g., cement content and water to cement ratio) [Chang 2004], [Papadakis 1989], mineral
66 admixtures [Hui-Sheng 2009] [Papadakis, 1999 and 2000] [Younsi 2011], exposure
67 conditions (e.g., temperature (T) [Saetta 1993] and external relative humidity (RH) [Houst
68 1983] [Papadakis, 1989]).

69 Because carbonation takes place throughout the life cycle of concrete, accurate assessment of
70 its progress is essential to predict the initiation of steel corrosion. To achieve this, the
71 condition of the concrete cover of structures must be surveyed at regular intervals in order to
72 plan maintenance. The most common technique used for measuring carbonation depth is the
73 semi-destructive coring method [RILEM CPC-18]. Phenolphthalein is sprayed on the fresh
74 cores obtained [Chang 2006, Villain 2006]. Phenolphthalein is an organic compound used as a

75 pH indicator: it is colorless at low pH values (around pH 9) but has a characteristic purple or
76 magenta color at pH values exceeding 10.5.

77 Testing is carried out at structure level with a sufficiently representative number of
78 measurement points, requiring a large variety of core samples [Breysse, 2017]. For improved
79 conservation of structures, non-destructive survey techniques must be favored as they can be
80 used to detect and characterize defects or damage without the need for coring [Bungey 2006].

81 The objective of this research is to examine the sensitivity to the presence of carbonation in
82 concrete structures of two currently available non-destructive methods: the Torrent
83 permeameter and the Wenner resistivimeter. Carbonation affects the microstructure of
84 concrete by reducing porosity [Nagla 1997, Auroy 2015] because the volume of hydrates
85 increases by an average of 11.7% [Song and Kwon 2007]. As the carbonation front
86 progresses, an increasing number of pores become clogged and reduce porosity in the depth of
87 carbonated concrete. [Porosity is one factor among others \(e.g. water content and rebars\)](#)
88 [affecting resistivity measurements in cementitious materials](#). Sbartai et al. [Sbartai 2007] have
89 demonstrated that resistivity increases when the W/C ratio of the studied concrete decreases,
90 leading to decreased porosity. A similar trend was observed by Lübeck et al. [Lübeck 2012]
91 after measuring concrete specimens with different water to binder ratios. As regards
92 permeability, some studies addressing the problem of permeability measurements using the
93 Cembureau method have shown that permeability decreases with the porosity of the studied
94 concrete [Hui-Sheng 2009] [Djerbi 2008 and 2013]. This trend is also reflected by
95 permeability measurements performed using the Torrent permeameter: Romer has measured
96 greater permeability values in mortars with a W/C ratio of 0.6 than in mortars with a W/C
97 ratio of 0.35 [Romer 2005] and the same tendency was also found by Neves [et al.](#) [Neves
98 2012]. The results presented by Neves [et al.](#) show that the permeability values obtained using
99 the Torrent method decrease as compressive strength rises and that porosity therefore

100 decreases [Neves 2015]. Sena da Fonseca *et al.* found a relation between Torrent air-
101 permeability and open porosity measured on stones [Sena da Fonseca 2015]. So it can be
102 assumed that the permeability of carbonated concrete is bound to decrease and that,
103 conversely, its resistivity may increase. We therefore selected two already available non-
104 destructive methods: the Wenner resistivimeter [Polder 2001] used to measure concrete
105 resistivity and the Torrent permeameter [Torrent, 1992] used to measure surface permeability.
106 In situ measurements were carried out on structures that were never completely dry for
107 auscultation. Depending on the weather conditions, the saturation *degree* of concrete may
108 differ. Because resistivity and permeability are both sensitive to concrete moisture content,
109 the sensitivity must be taken into account in the measurement analysis of both devices. The
110 influence of the resistivity as a function of the saturation level has been investigated by
111 Sbartai *et al.* [Sbartai 2007] and the results demonstrate that concrete electrical resistivity
112 decreases when saturation level increases. Resistivity varies between 54 and 960 $\Omega.m$ but
113 cannot be measured when the saturation level is less than 60%. Similar results are found in
114 other studies. In [Saleem 1996], resistivity ranges from 80 to 780 $\Omega.m$ and, the lower the
115 water content, the higher the resistivity. At a mass water content of about 1.5%, the resistivity
116 cannot be measured because the concrete slab is too dry to allow the current to flow within the
117 sample. The work of Lopez and Gonzalez [Lopez and Gonzalez, 1993] underlines the effect
118 of the pore saturation level in relation to resistivity. They carried out tests on mortars with a
119 W/C ratio of 0.5. The resistivity values changed within a narrow range when the pore
120 saturation level varied between 60 and 100%. Then, between 60 and 30%, the resistivity
121 increased sharply, up to a limit corresponding to a saturation level at which measurement was
122 impossible. Recent studies have improved the resistivity techniques to monitor water and
123 chloride ingress in concrete by using a multi electrode resistivity system [Du Ploy 2015,
124 Lecieux 2015, Fares 2018].

125 Gas permeability is a transport property characterizing [gas flow under a pressure gradient](#) and
126 is used to determine the speed with which a gas (potentially an aggressive gas like carbon
127 dioxide) may penetrate into concrete. Air permeability is affected by the concrete moisture
128 content and the concrete saturation level has been shown to have an effect on transport
129 properties. For instance, the air permeability of a concrete specimen, measured using the
130 Cembureau method, increases when the saturation level decreases [Villain 2001, Picandet
131 2001]. Kameche et al. [Kameche 2014] confirmed this influence [and the present study](#) was
132 conducted to examine the intrinsic permeability variations of CEM II concrete materials
133 according to the degree of saturation, from a saturated state to a completely dry state. Because
134 gas intrinsic permeability decreases when the saturation level increases, Cembureau
135 measurements are not possible with saturation rates above 80%. Romer conducted an
136 experimental study to assess the Torrent and Cembureau methods in CEM I mortar samples
137 prepared with different cement contents [Romer, 2005]. The tests were carried out by varying
138 the relative humidity of the samples via processing at different ambient conditions. The
139 results thus obtained confirm that the permeability values measured using both Cembureau
140 and Torrent methods increase as the samples become drier. However, the study does not
141 determine the sample saturation level.

142 It thus appears from the studies listed above that both resistivity and permeability decrease
143 when the saturation level increases. Moreover, resistivity measurements are possible with
144 saturation rates above 30% (water content higher than 1.5%) whereas Cembureau
145 permeability measurements are only possible with rates below 80%.

146 Permeability is a transport property depending on the porosity of the material studied.
147 Because carbonation decreases porosity, the surface permeability of carbonated concrete
148 measured using the Torrent permeameter can be expected to change. As regards water
149 permeability, the water flow is weaker in carbonated than in non-carbonated concrete [Song

150 and Kwon, 2007]. Auroy *et al.* underline a decrease in intrinsic permeability after carbonation
151 for CEM I Portland cement [Auroy, 2015].

152 Similarly, because resistivity is affected by the material microstructure, variations in
153 resistivity can be expected according to the carbonation depth. However, the literature
154 reviewed for this paper contains no research on the resistivity and permeability of carbonated
155 concrete specimens using Wenner's and Torrent's methods. The present study, therefore,
156 addresses *carbonation and moisture* effects on resistivity and permeability measurements in
157 terms of both quality and quantity *in laboratory conditions*. *It is also important to note that*
158 *rebar close to surface affects the resistivity. We chose to avoid this effect as it is difficult to*
159 *evaluate, except maybe by using a numerical model for the determination of apparent*
160 *resistivity* [Nguyen 2017].

161 Using the Wenner resistivimeter and the Torrent permeameter, and taking account of the
162 sensitivity of the measurement equipment, resistivity and permeability results measured in
163 concrete slabs made of the same mixture, with varying carbonation depths and saturation
164 levels ranging from a dry state to a saturated state, were determined. The experimental results
165 are analyzed below and translated into laws considering the dispersion of the measurement
166 values. The objective of this analysis is the simultaneous use of both non-destructive methods
167 (NDT) to *assess* saturation level and carbonation depth in real structures. Finally, the laws of
168 correlation established were validated using a concrete wall made of the same concrete mix as
169 the experimental slabs.

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175 2 Materials and experimental program

176 2.1 Concrete specimens

177 The concrete mix was composed of CPA-CEM I 52.5 Portland cement with a water/cement
178 ratio of 0.8 to accelerate the carbonation process (Table 1). Eleven slabs (rectangles 50 x 25
179 and 12 cm thick) were prepared from a single batch of concrete in a laboratory in Toulouse
180 (France): nine were cast for non-destructive testing, one was used for determining the
181 physical and mechanical properties and the last one was sealed on five faces and put into the
182 carbonation chamber to monitor carbonation depth. The concrete mixtures were cast in plastic
183 molds and compacted under vibration. After casting, the slabs were stored in a room at 20 °C
184 with about 95% relative humidity (RH) for 24 h until demolding, after which they were cured
185 in water at 20 °C for 28 days.

186 After 28 days, two slabs were used to assess the mechanical and physical properties of the
187 concrete. Cylindrical cores were extracted from these slabs to drive these tests. The results are
188 summarized in Tables 2 and 3. Open porosity was measured using the water saturation
189 method on three specimens. Three specimens were tested under axial compressive loading
190 conditions with measurement of lateral and axial displacements, and three other discs were
191 sealed with two layers of adhesive aluminum tape to ensure a one-dimensional gas flow
192 through the discs. These specimens were oven-dried at 105 °C to constant weight before
193 permeability testing was conducted using the Cembureau device.

194

Constituents (kg/m ³)	OPC C1
Cement CEM I 52.5 N CE CP2 NF	240
Siliceous Sand 0/2 or 0/4	941
Siliceous aggregates 4-14 or 10-14	1019
Water	193
Superplasticizer	0.96
W/C	0.8
Slump (cm)	14

195

Table 1: Mix proportions of concrete

Properties	OPC C1
Dry apparent density (kg/m ³)	2 222
Open porosity measured by water saturation method (%)	18.3
Cembureau apparent permeability with an injection pressure of 0.5 bars measured in dried specimen (10 ⁻¹⁶ m ²) (= K _{ref,C})	7.71

197

Table 2: Physical and transport properties (average of three measurements)

198

Mechanical properties (28 days)	OPC C1
compressive strength (MPa)	21.5
Modulus of elasticity (MPa)	24927
Poisson ratio	0.208

199

Table 3: Mechanical properties at 28 days (average of three measurements)

200

201

2.2 Carbonation procedure

202

The nine slabs intended for non-destructive testing were referenced as N or T (Table 4). After exposure to carbonation, the slabs referenced N were stored in Nantes (France) and those referenced T, in Toulouse.

205

After a 28-day residence time in water, the slabs were oven-dried at 80 °C until constant weight was reached. The dry mass, W_d , was used to calculate the water content at time t

207

(Equation 1), which, in turn, was used to calculate the degree of saturation at time t (Equation

208

2). At the end of the drying phase, the slabs were stored in laboratory conditions. The four

209

slabs referenced as 1 (C1-1-7N, C1-1-8N, C1-1-1T, C1-1-2T) were completely sealed with

210

two layers of adhesive aluminum tape to prevent carbonation. The slabs referenced C1-2N,

211

C1-3N, C1 4N, C1-2T, and C1-3T were sealed on five faces only, to ensure a one-

212

dimensional carbonation processing from one side of the slab only (50 cm x 25 cm). These

213

slabs were placed in a chamber at 20 °C, with a relative humidity of 65% and a CO₂ content

214

of 50% to accelerate the carbonation process. The core samples were extracted from the

215 specific sampling slab at the end of the curing phase and stored with the slabs in the
 216 laboratory. They were also placed in the carbonation chamber to monitor carbonation
 217 progress, just like the slabs. However, during this phase, the different core samples were
 218 regularly broken and immediately sprayed with the phenolphthalein color indicator so as to
 219 assess the carbonation depth at a given point of time. When the different desired carbonation
 220 depths had been reached on the control core samples, the slabs were removed from the
 221 chamber and immersed in water to stop carbonation and to ensure complete saturation of the
 222 slabs.

223 The real carbonation depths measured after completion of the whole experimental procedure
 224 using NDT techniques, are presented in Table 4.

225

Slab reference	Expected carbonation depth (mm)	Measured carbonation depth d_c (mm) (cf. Figure 1)
C1-1-7N	0	0
C1-1-8N	0	0
C1-2N	10	9.1
C1-3N	20	18.2
C1-4N	30	27.3
C1-1-1T	0	0
C1-1-2T	0	0
C1-2T	10	10.5
C1-3T	20	17

226

Table 4: Expected and measured carbonation depths

227

228 2.3 Experimental procedure

229 The operating method consisted in varying the slab water content in order to obtain
 230 permeability and resistivity correlation curves according to the saturation level. After
 231 saturation, different phases of drying were undertaken in order to achieve measurements with

232 targeted water contents corresponding to identical saturation levels for all the slabs. For that
233 purpose, the slabs were placed in a drying oven at 80 °C and dried while their weight loss was
234 monitored. It was assumed that the concrete was not modified at 80 °C, since ettringite is
235 considered to dehydrate at a temperature higher than 80 °C [Zhou and Glasser 2001] and
236 therefore would have remained almost stable at 80 °C. When the targeted mass was obtained
237 and the drying phase completed, the slabs were hermetically sealed in airtight bags for forty
238 days to balance the humidity level of the slabs and prevent natural carbonation. Their mass
239 was measured regularly to leak-check the bags. Once the slabs were taken to be homogenized,
240 the slab mass, $W(t)$, was measured again. Then, resistivity and permeability measurements
241 were carried out. The water content was determined from Equation 1:

$$242 \quad w(t) = (W(t) - W_d) / W_d \quad (1)$$

243 where $w(t)$ is the water content at time t , $W(t)$ is the mass of the slab at time t (kg) and W_d is
244 the mass of the dried slab (kg).

245 The degree of saturation at time t is obtained from Equation 2 as:

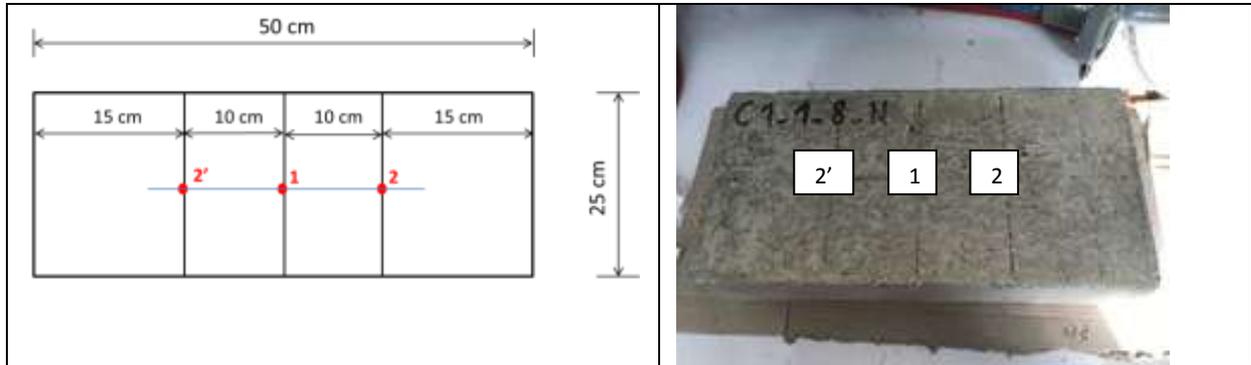
$$246 \quad S(t) = w(t) / w_{\text{sat}} \quad (2)$$

247 where w_{sat} is the water content of the saturated slabs.

248

249 For each measurement method (Wenner resistivimeter and Torrent permeameter), a total of
250 ten measurements per test point and saturation level were performed. Measurements were
251 carried out in the center of all the slabs (Point 1 in Figure 2). However, in order to check slab
252 homogeneity and measurement sensitivity to side effects, measurements were also carried out
253 on either side of Slab C1-1-8-N center (Points 2 and 2' in Figure 2). The measurements were
254 made first at point 1, then at point 2 and finally at point 2' before returning to spot 1. So there
255 was enough time between consecutive measurements in the same spot to allow vacuum
256 dissipation.

257 The Wenner resistivity measurements were first carried out to determine the resistivity
 258 values, which were afterwards used for the Torrent surface permeability measurements
 259 [Torrent 1992].



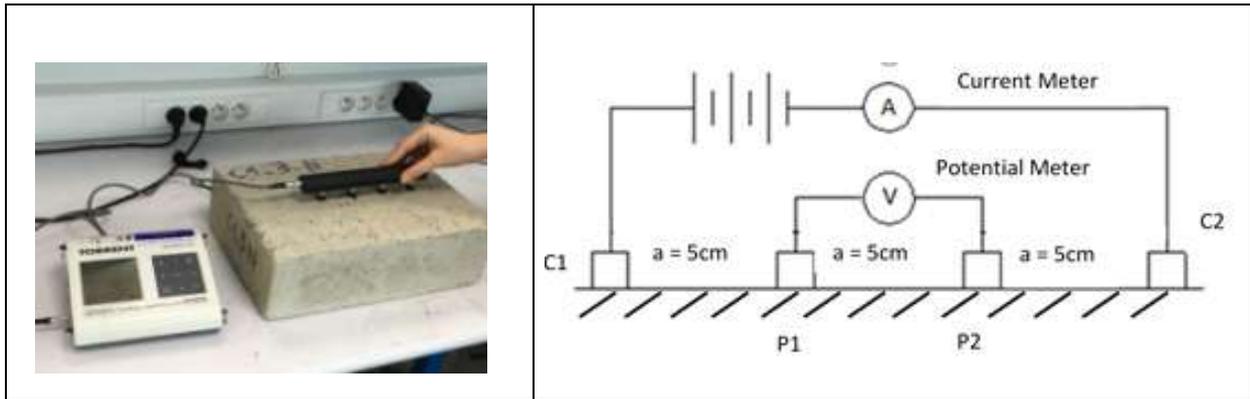
260 *Figure 2: Location of measurement points on the slabs*

261
 262 The Wenner resistivimeter is a measurement device using Wenner protocol to determine the
 263 apparent resistivity of concrete facings. Measurements are assumed to be carried out on a
 264 semi-infinite homogeneous material. The measurement device is called a Wenner
 265 resistivimeter because of the electrode arrangement, in which the distance interval between
 266 the electrodes, called a , is the same, with $a = \overline{C_1P_1} = \overline{P_1P_2} = \overline{P_2C_2}$ (Figure 3). The device used
 267 in this work had a distance interval of 5 cm. First, an electric current, I , is injected between
 268 electrodes C_1 and C_2 . Then, the electrical potential is measured between electrodes P_1 and
 269 P_2 . The apparent resistivity is calculated by the control acquisition unit, based on the
 270 following formula:

271
$$\rho = 2 \pi a \frac{V}{I} \quad (3)$$

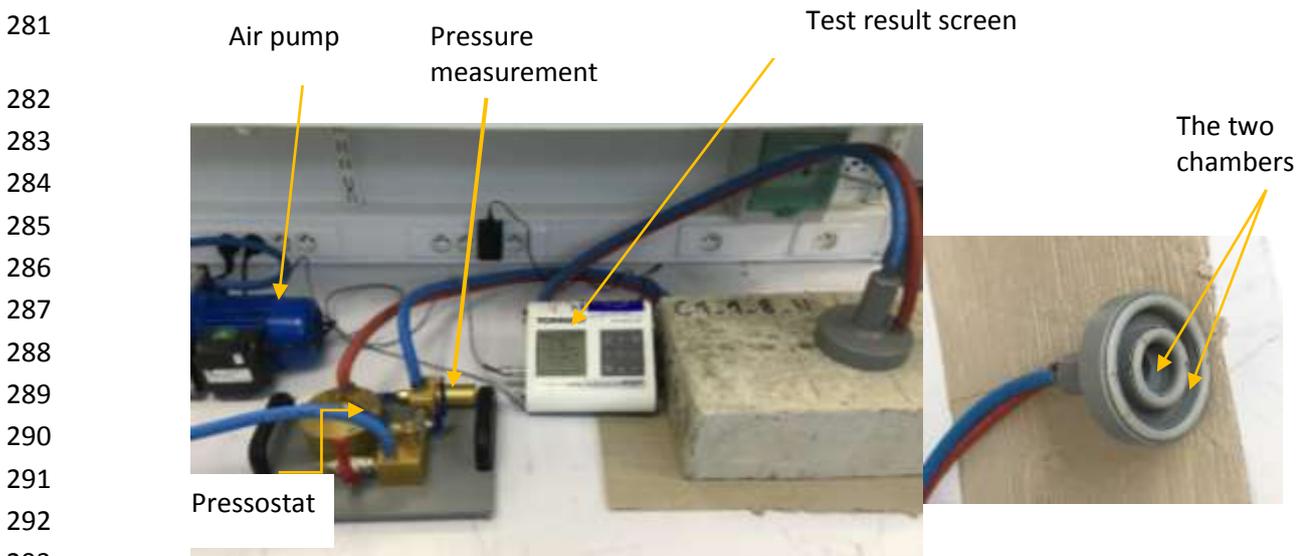
272 where ρ is the resistivity in $\Omega.m$, a is the distance interval between the electrodes in m , V is
 273 the voltage in volts and I is the current intensity injected into the sample in amperes.

274



275 *Figure 3: Wenner resistivity measurements*

276
 277 After the resistivity measurement was finished, the Torrent permeability was measured, if
 278 possible, depending on the slab saturation level. The test principle is to create a vacuum inside
 279 the test chamber using a vacuum pump and then disconnect the pump when the desired
 280 pressure is reached (Figure 4).



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 294 *Figure 4: Torrent permeameter*

295
 296 The rate of increase of pressure inside the vacuum cell can be measured and the air
 297 permeability can be calculated according to the following formula:

$$298 \quad K = \left(\frac{V_c}{A}\right)^2 \cdot \frac{\mu}{2 \varepsilon P_a} \left[\frac{\ln\left(\frac{P_a + \Delta P}{P_a - \Delta P}\right)}{\sqrt{t} - \sqrt{t_0}} \right]^2 \quad (4)$$

299

300 with: K : Torrent gas permeability coefficient (m^2),
301 μ : Air dynamic viscosity at 20 °C ($2.0 \cdot 10^{-5}$ N.s/m²),
302 V_c : Capacity of the inner chamber and of the elements, through which air flows during
303 the filling phase ($V_c = 222 \cdot 10^{-6}$ m³),
304 ϵ : Concrete porosity introduced in the data (18.3 %, cf. Table 2).
305 A : concrete cross-section where air flows in the vacuum cell ($19.6 \cdot 10^{-4}$ m²),
306 ΔP : Pressure difference in the inner chamber in N/m²,
307 P_a : Atmospheric pressure in N/m²,
308 t_0 : Test start time (60 s),
309 t : Test duration (< 720 s).

310

311 3 Results

312 3.1 Resistivity results

313 Resistivity measurements at the three points on a given slab showed little scatter in the results,
314 indicating that the concrete was homogeneous over the whole slab volume. It was concluded
315 that the saturation level of the slab was spatially homogeneous on the surface investigated.
316 Moreover, resistivity values were not influenced by side effects. Consequently, only the
317 average of the different measuring points appears in Figures 5 to 8. The standard deviations
318 were calculated from thirty measurements (ten measurements for Point 1, ten measurements
319 for Point 2 and ten measurements for Point 2').

320 For saturation levels below 41%, measurements proved impossible for the most carbonated
321 slab because it was too dry to allow electricity to flow freely between the electrodes.

322 Whatever the carbonation depth reached, Figure 5, 6, 7 and 8 show a lower resistivity when
323 the sample saturation level increases. The trend observed in Figures 6 and 7 for non-
324 carbonated samples has been highlighted by many authors [Sbartai 2007, Saleem 1996, Lopez

1993]. When the saturation level decreases, the concrete liquid phase gradually changes to a discontinuous pattern that makes ion conduction more difficult. Resistivity values then increase sharply. In non-carbonated slabs, resistivity increases by a factor of six between saturated samples and samples with a 41% saturation level. This explains the non-linear behavior of the electrical resistivity in relation to the variations of concrete saturation levels. Carbonation depth also affects resistivity. For the same saturation level, resistivity increases because of concrete structural changes due to carbonation reactions. The decrease in porosity induced by carbonation increases the material compactness, resulting in a less prevalent liquid phase. The current then flows less freely and resistivity increases.

334

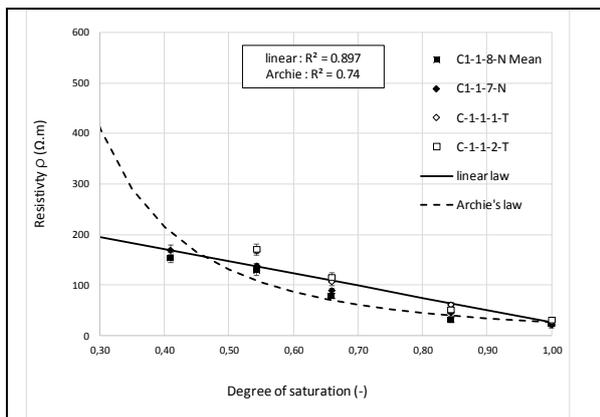


Figure 5: Resistivity versus saturation degree for non-carbonated slabs

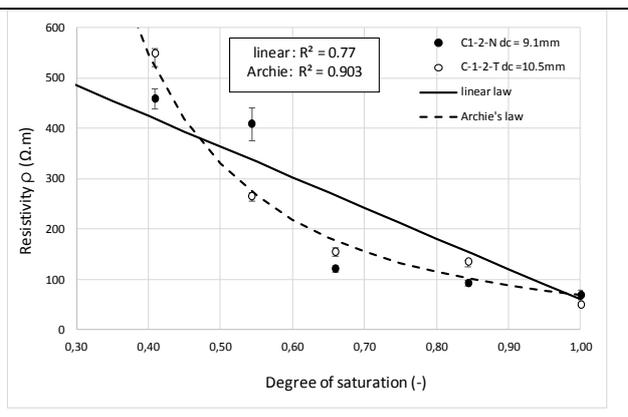


Figure 6: Resistivity versus saturation degree for carbonated slabs C1-2-N and C1-2-T ($d_{cmean} = 9.8 \text{ mm}$)

335

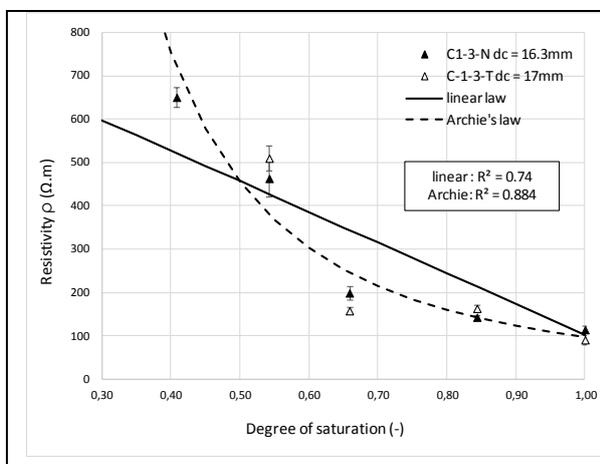


Figure 7: Resistivity versus saturation degree

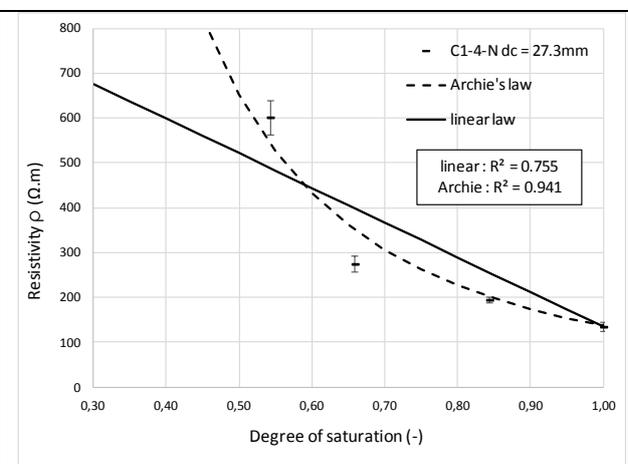


Figure 8: Resistivity versus saturation degree

<i>degree for carbonated slabs C1-3-N and C1-3-T ($d_{cmean} = 16.65 \text{ mm}$)</i>	<i>for carbonated slab C1-4-N with $d_c = 27.3 \text{ mm}$</i>
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336 Some mathematical laws are now examined for best fitting of the experimental points. We
337 first select a linear law because the results achieved for the non-carbonated slabs, within the
338 saturation level range for which measurements are possible, follow a linear trend. Then the
339 linear equation to determine the mean resistivity of saturated slabs when the degree of
340 saturation is 100% is taken as:

$$341 \quad \rho = a * (1 - S) + b \quad (5)$$

342

343 In the case of non-carbonated and fully saturated slabs, b is the reference value ρ_{ref} , called the
344 reference resistivity. This value corresponds to the mean resistivity obtained on non-
345 carbonated slabs in saturated conditions (C1-1-8-N, C1-1-7N, C1-1-1-T, C1-1-2-T). Here, the
346 value of b is 27.627 $\Omega.m$.

347 In the case of carbonated slabs, b is the mean resistivity calculated from the two saturated
348 slabs ($S=100\%$). For a carbonation depth of 27.3 mm, the value of b is obtained using Slab
349 C1-4-N only. The values of a obtained by fitting the experimental data using Equation 5 are
350 reported in Table 6.

351

352 The empirical Archie's law [Archie 1942] is also used to describe the general trend identified
353 in these figures. This law describes the dependency of resistivity on the degree of saturation
354 (S), porosity (ϕ) and resistivity of the composition pore solution (ρ_{sol}) as:

$$355 \quad \rho = \rho_{sol} * S^{-n} \phi^{-m} \quad (6)$$

356 Parameters m and n are usually regressed over the experimental data.

357

358 To use this law, some parameters must be set. The pore solution resistivity is assumed to be
359 constant throughout the carbonation process. However, it is reasonable to believe that the

360 change in the cement matrix due to the dissolution of the portlandite modifies the pore
 361 solution and therefore its conductivity.

362 The conductivity of the pore solution ($\sigma_{sol}=1/ \rho_{sol}$) can be expressed as:

$$363 \quad \sigma_{sol} = \sigma_{wat} + \Sigma(C_i * \lambda_i) \quad (7)$$

364 where $\sigma_{wat} = 10^{-5}$ S/m , corresponding to the water conductivity as found in [Shi 2003]

365 C_i ionic content (mol/m³)

366 λ_i ionic molar conductivity (S.m²/mol)

367

368 The conductivity of the pore solution is assessed by combining data by Andersson et al.
 369 [Andersson 1989] and Nguyen [2006] (Table 5). Two solution conductivities are calculated:
 370 $\sigma_{sol} = 8.92$ S/m with the values by Nguyen and $\sigma_{sol} = 6.41$ S/m with the values by
 371 Andersson. Both these authors used very similar Portland cement but the mixes were
 372 different. The mean value ($\sigma_{sol} = 7.66$ S/m) is used to calculate the resistivity of the pore
 373 solution of the sample tested. This value is of the same order of magnitude as the values found
 374 in the literature, although the literature values obviously depend on cement type and water to
 375 cement ratios [Sanish 2013, Sant 2011, Neithalath 2006].

376

Ion	Ionic molar conductivity (mS.m ² /mol)	Ionic content (mol/m ³) [Nguyen 2006]	Ionic content (mol/m ³) [Andersson 1989]
Na ⁺	5,01	100	42.3
K ⁺	7.35	272	161.1
Ca ²⁺	11.9	2.6	2.2
Cl ⁻	7.63	0.5	Not evaluated
OH ⁻	19.86	321.4	251.2 (calculated using measured pH)

377 *Table 5: Values used to calculate the conductivity of the pore solution*

378

379 In order to determine the factor n, which is assumed to be constant for both carbonated and
380 non-carbonated slabs, the data obtained on non-carbonated slabs are used. In this case, the
381 factor m is calculated using Archie's law for S=100% ($\rho_{ref} = \rho_{sol} * \phi^{-m_{ref}}$). We then have
382 $m_{ref} = 3.153$ with $\rho_{ref} = 27.627 \Omega.m$. The factor n is therefore determined by fitting the
383 experimental data of the non-carbonated slabs using Archie's law as: $n = 2.24$ (Figure 5). For
384 the carbonated slabs (Figures 6, 7 and 8), n is kept constant and only m is adjusted to achieve
385 the best possible fitting with the experimental data because it is assumed to depend on the
386 microstructure, which changes during carbonation.

387 Table 6 displays the different law parameters and determination coefficients obtained. Both
388 laws can be used to represent the trend obtained because the determination coefficients are
389 correct in both cases. The determination coefficients given by the linear law, however, are
390 lower, except on non-carbonated slabs, as the linear law does not represent points obtained for
391 low saturation levels very accurately. It seems likely that, for a dry material, resistivity tends
392 toward a very high value. This trend is thus best represented by Archie's law.

393

		a/n	b/m	Determination coefficient R ²
Non-carbonated slabs	Linear	238.16	27.627	0.897
	Archie	2.24	3.153	0.74
$d_c \text{ mean} = 9.8 \text{ mm}$	Linear	725.955	59.9	0.77
	Archie	2.24	3.70	0.903
$d_c \text{ mean} = 16.65 \text{ mm}$	Linear	864.852	102.63	0.74
	Archie	2.24	3.89	0.884
$d_c = 27.3 \text{ mm}$	Linear	913.16	135	0.755
	Archie	2.24	4.10	0.941

394 *Table 6: a and b (linear law), n and m (Archie's law) and corresponding determination*
395 *coefficient R²*

396

397 The relations of coefficients a and b with mean carbonation depth are described as a
398 logarithmic function (Equation 8) with $R^2 = 0.984$ and a linear function (Equation 9) with R^2

399 = 0.982, respectively. As regards Archie's law, the plot of coefficient m versus mean
400 carbonation depth is described by a linear function with $R^2 = 0.91$ (Equation 10).

$$401 \quad a = 91.645 * \ln(d_c) + 442.03 \quad (8)$$

$$402 \quad b = 4.0198 * d_c + 27.627 \quad (9)$$

$$403 \quad m = 0.0389 * d_c + 3.153 \quad (10)$$

404 By combining relationships 5 and 6 with Equations 8, 9 and 10, we obtain the laws describing
405 electrical resistivity versus carbonation depth and saturation degree, respectively (Equations
406 11 and 12):

$$407 \quad \rho = (91.645 * \ln(d_c) + 442.03) * (1 - S) + (4.0198 * d_c + 27.627) \quad (11)$$

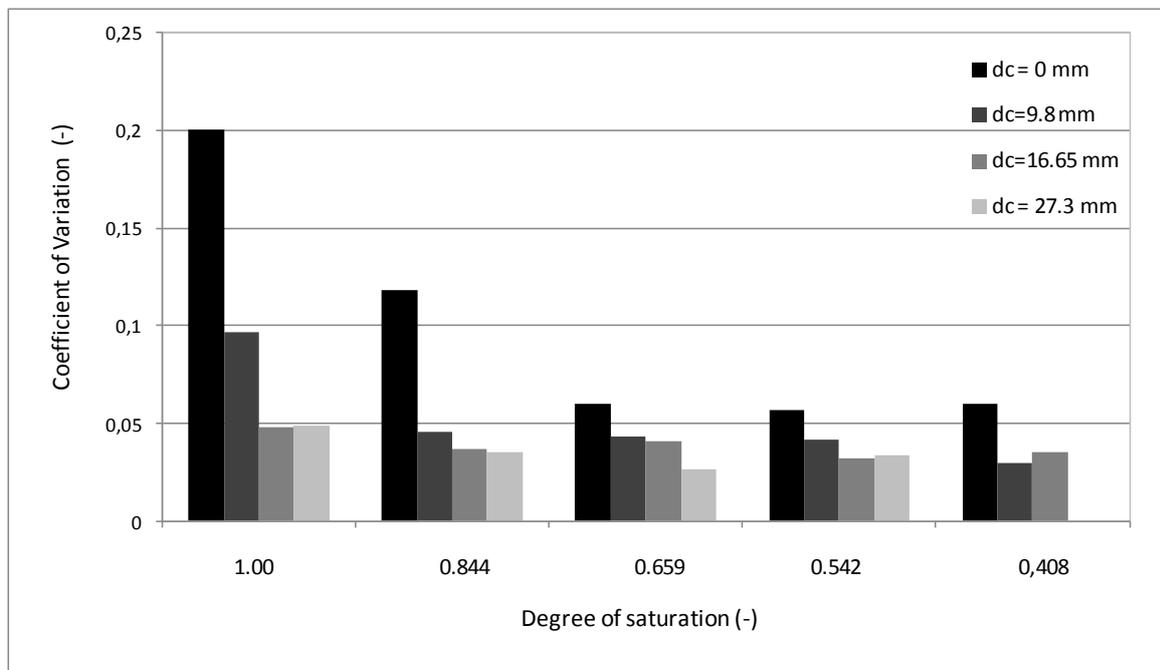
$$408 \quad \rho = \rho_{sol} * S^{-2.24} \phi^{-(0.0389*d_c+3.153)} \quad (12)$$

409 where d_c is the carbonation depth in mm and ρ the Wenner resistivity ($\Omega.m$)

410

411 The coefficients of determination obtained for the linear law parameters are higher than that
412 obtained for parameter m of Archie's law. These laws may be used for the calculation of the
413 saturation level from a resistivity measurement with knowledge of the carbonation depth. This
414 depth would have been determined, for instance, by spraying phenolphthalein on a freshly
415 drilled core sampled from the structure. Carbonation depth determination is faster than
416 saturation level determination because it can be read immediately after sampling without
417 waiting for the complete drying needed for saturation level measurements. However, the laws
418 established here apply only to concrete with similar porosity (about 18%) and mixed with
419 CEM I cement. Solution resistivity and carbonation process both depend on the type of
420 cement and any addition modifies the chemical reactions. These laws should also consider the
421 measurement error aspects. In order to seriously take the standard deviations displayed in
422 [Figures 5, 6, 7 and 8](#) into account, [Figure 9](#) presents the Coefficient of Variation (CoV),

423 corresponding to the standard deviation divided by the average of the values measured, for all
 424 the saturation levels. CoV values are very low (lower than 10% when the value obtained from
 425 the saturation measurements carried out on the non-carbonated slabs is eliminated). Moreover,
 426 this maximum value of 20% is of the same order of magnitude as the CoV calculated from
 427 laboratory measurements (approximately 18%) [Ait-Mokhtar, 2013]. It may be recalled that
 428 measurements appear reliable here, because the lower the CoV value, the higher the
 429 measurement accuracy. The results obtained on the non-carbonated slabs correspond to the
 430 lowest resistivity values and, hence, to higher CoV values. This analysis suggests that the
 431 Wenner measurements carried out using this device can be reproduced.



432
 433 **Figure 9:** Coefficient of variation of the resistivity measurements as a function of saturation
 434 degree and carbonation depth

435
 436 **3.2 Air permeability results**

437 **Permeability measurements at the three points on a given slab showed scatter in the results.**
 438 **The differences observed cannot be attributed to the heterogeneity of the concrete material as**
 439 **all the resistivity measurements performed on the same slab for a given saturation level are**

440 almost identical whatever the measurement point. Because side effects have not been
441 demonstrated, the three point averages are presented with, on either side, the range defined by
442 the standard deviation calculated from all the values (30 measurements). Moreover, on
443 different concrete compositions, Neves *et al.* showed that, if the average of a set is used as the
444 representative value, it is possible to distinguish between different concrete mixes and
445 different curing (for the same mix) [Neves 2012].

446 Figures 10 through 13 show that, for a given carbonation depth, gas permeability decreases
447 when the saturation level increases and also decreases when carbonation depth increases.
448 Permeability also varies greatly in the slabs, which are supposed to be of the same concrete
449 and in the same saturation state. Figure 10 shows that, when $S_r = 15\%$, permeability ranges
450 from 17 to 25.10-16 m^2 , i.e. an increase of almost 50%. Although measurements are not
451 possible on the fully saturated samples, they can, nevertheless, be performed up to 84%.
452 Above this saturation rate, gas can no longer flow freely because of water molecule continuity
453 in the concrete porous network. Concrete relative humidity reduces pore interconnectivity
454 and, therefore, affects its permeability. The permeability vs. saturation level curve has already
455 been assessed in the literature for non-carbonated materials using Cembureau measurements
456 carried out on different concrete types [Kameche 2014, Abbas 1999]. These authors have
457 established a logarithmic law to describe, as far as possible, the experimental results regarding
458 intrinsic permeability as a function of saturation level for different sample sizes.
459 Measurements are possible up to approximately 80% of the saturation level. As regards the
460 work of Abbas *et al.* [Abbas 1999], a linear law best represents the results obtained for the
461 apparent permeability measurements at different pressures as a function of the saturation
462 level, with a saturation threshold of 90%. It should, however, be noted that the measurement
463 variation ranges of both studies are larger than that obtained in the present paper using the
464 Torrent permeameter, which results in a logarithmic display of their results. The present

465 results, on the other hand, are displayed on a linear scale for viewing comfort. They are fitted
 466 with a linear law for all the carbonation depths reached by imposing zero permeability as a
 467 condition for the saturated samples ($S = 100\%$). This law is described by Equation 13. As
 468 regards dry, non-carbonated slabs, the reference value, $K_{ref,T}$ is imposed as the value for a.
 469 This value corresponds to the average obtained from the Torrent permeability measurements
 470 carried out on the dry non-carbonated Slabs C1-1-8-N, C1-1-7-N, C1-1-1-T and C1-1-2-T, is
 471 $27.34 \cdot 10^{-16} \text{ m}^2$.

$$472 \quad K = a * (1 - S) \quad (13)$$

473
 474 The coefficients of determination are correct in view of the large standard deviations, which
 475 make it possible to confirm that the linear laws express Torrent permeability evolution
 476 satisfactorily as a function of the saturation level.

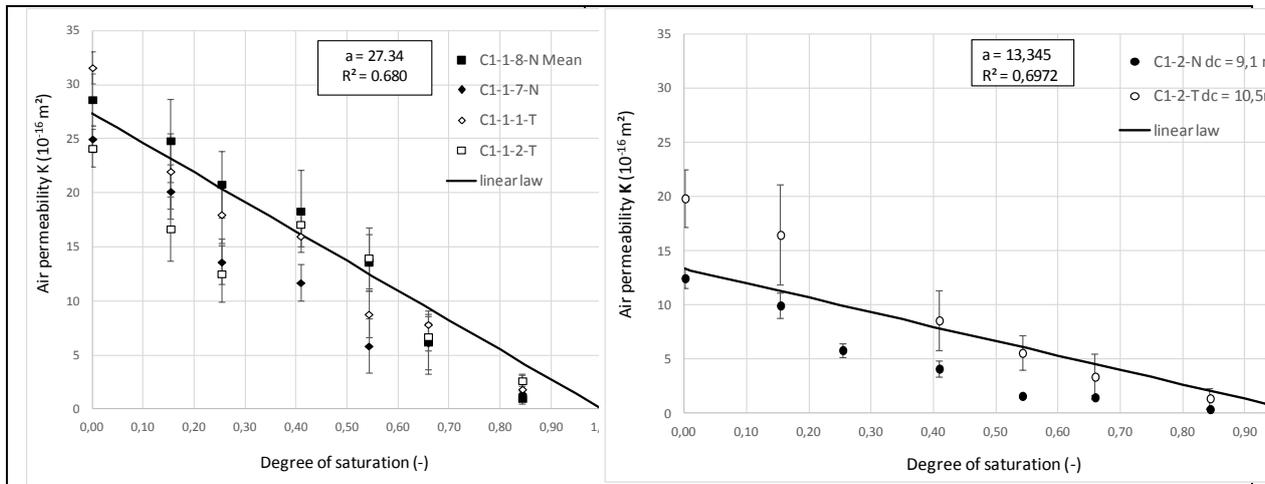


Figure 10: Torrent permeability versus saturation level for non-carbonated slabs

Figure 11: Torrent permeability versus saturation level for carbonated slabs C1-2-N et C1-2-T ($d_{c \text{ mean}} = 9.8 \text{ mm}$)

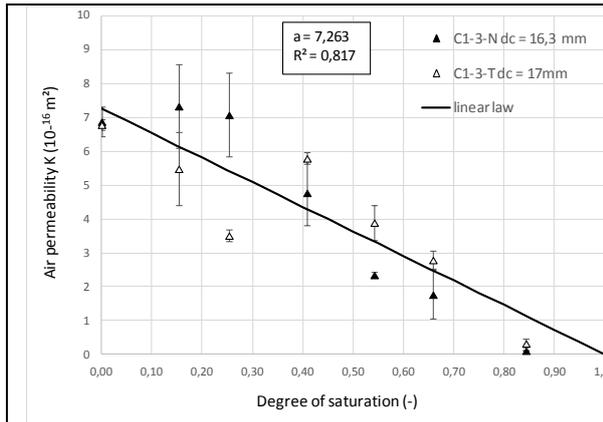


Figure 12: Torrent permeability versus saturation level for carbonated slabs C1-3-N et C1-3-T ($d_{cmean} = 16.65$ mm)

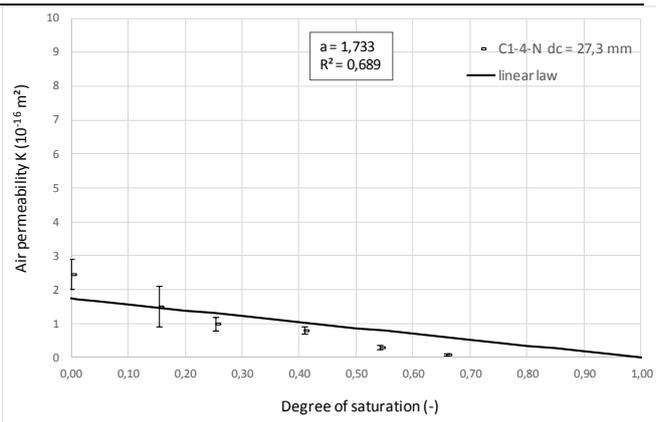


Figure 13: Torrent permeability versus saturation level for carbonated slabs C1-4-N ($d_c = 27.3$ mm)

477 Equation 14 describes coefficient a versus carbonation depth and is then introduced into
 478 Equation 15 to obtain Torrent permeability as a function of carbonation depth and saturation
 479 degree. Law 14 is obtained with a good determination coefficient $R^2 = 0.964$. Both equations
 480 take the form:

$$481 \quad a = 27.34 * e^{-0.0935*d_c} \quad (14)$$

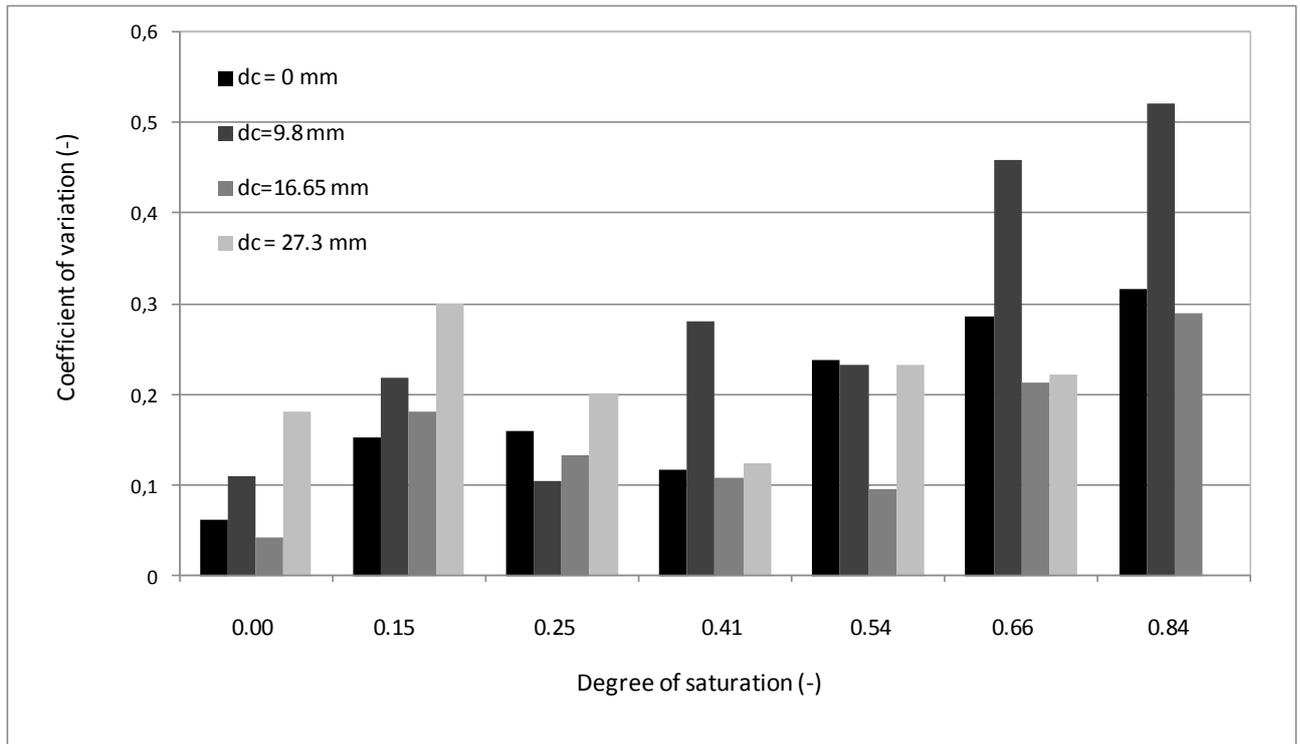
$$482 \quad K = (27.34 * e^{-0.0935*d_c}) * (1 - S) \quad (15)$$

483 where d_c is the carbonation depth in mm and K is the Torrent measurement (10^{-16} m²)

484

485 This law (15) could be used to calculate the saturation level from a permeability measurement
 486 with knowledge of the carbonation depth from phenolphthalein spraying on the fresh core
 487 sampled from the concrete structure.

488 In view of Figures 10 through 13, standard deviation appears to decrease when saturation
 489 level increases (only beyond a saturation level of 15%) to reach the lowest values for samples
 490 with an 84% saturation level. However, this observation is surprising since permeability
 491 measurements were conducted on completely dry samples, a condition required for correct
 492 measurement of the gas permeability. So, the coefficients of variation according to the
 493 saturation levels for the four carbonation depths studied are displayed in Figure 14.



494

495 *Figure 14: Coefficient of variation of Torrent permeability measurements as a function of*
 496 *saturation degree and carbonation depth.*

497

498 The results presented in [Figure 14](#) are closer to expectations. Carbonation depth has no effect

499 on the measurements because trends observed in the carbonated slabs differ depending on the

500 saturation level. CoV, on the other hand, effectively increases with the degree of saturation. It

501 should be noted, however, that CoV could not be measured for $d_c = 27.3$ mm at an 84.1%

502 saturation level, which was at the device operating limit. Moreover, with this saturation level,

503 the coefficient of variation ranges between 30 and 50%. This high range raises questions as to

504 measurement reliability. With these saturation levels, the device operating limits are

505 exceeded, all the more so when the concrete is compact. A key idea of this analysis is that

506 saturation level S and carbonation depth d_c can be determined from the measured K and ρ by

507 combining Equation 15 with Equation 11 or 12. However, these established relationships

508 apply only if the concrete porosity is equivalent (about 18%) and the formulation uses CEM I

509 cement, as in this study. Resistivity and permeability measurements depend on the material

510 composition, which in turn affects the porosity and conductivity of the pore solution.

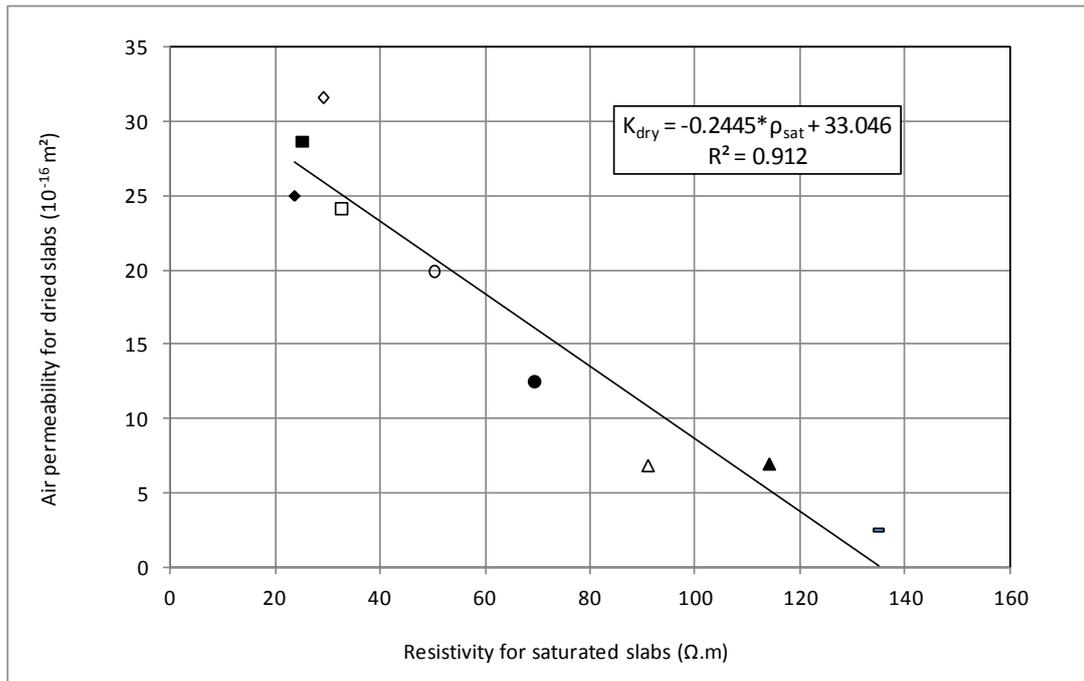
511 Moreover, the combination of the two laws is possible only if both measurements can be
512 performed simultaneously, i.e., when the concrete saturation level falls within the range 40-83
513 %, which is quite often the case where in situ concrete is concerned.

514

515 4 Result analysis

516 4.1 Correlation between resistivity and Torrent gas permeability

517 [Figure 15](#) shows the correlation between Torrent gas permeability measurements for dried
518 slabs ($S= 0\%$) and resistivity measurements carried out on saturated slabs ($S = 100\%$). This
519 comparison is possible since the saturation level is set aside as the impact of pore saturation is
520 canceled out. The symbols used are the same as in [Figures 5 through 8 and 10 through 13](#). A
521 linear correlation is observed between the two parameters. The slabs with the highest
522 permeability present the lowest resistivity. Both properties share some crucial pore structure
523 characteristics, such as total porosity, pore tortuosity and connectivity, of the cover concrete
524 subjected to carbonation. They are sensitive to the different phases occurring within pores:
525 gas permeability is linked with the characteristics of the gas phase and resistivity depends on
526 the liquid phase through its electrochemical composition. Nevertheless, a good linear
527 correlation is observed for the material studied here. The correlation established by Gui et al.
528 [Gui 2016] for a study conducted to examine gas permeability using the Cembureau device
529 and electrical conductivity using the high frequency alternating current method on laboratory
530 concrete specimens with different water to binder ratios and different admixtures is not as
531 good as the correlation proposed in this paper.



532

533 *Figure 15: Torrent permeability for dried slabs versus resistivity for saturated slabs*

534

535 4.2 Resistivity analysis

536 **Relative resistivity is considered because it could be useful to compare different concretes:** it

537 has been used by Gui et al. to study electrical conductivity and gas permeability of concrete

538 formulated with CEM I and blast-furnace slag cement [Gui, 2016]. Using a relative value for

539 resistivity and permeability could also be very useful for a modeling approach [Li, 2016].

540 Resistivity values are then processed after dividing them by the reference value ρ_{ref} . This

541 value can be considered as an intrinsic transport property since the impact of carbonation and

542 pore saturation is canceled out. This value is measured directly on the slabs using the Wenner

543 method. However, in future, taking the value measured on laboratory samples as the reference

544 value when selecting concrete type might be contemplated [Baroghel-Bouny, 2004; Aït-

545 Mokhtar, 2013].

546 We use the following relationship to fit the experimental data:

$$547 \quad \frac{\rho}{\rho_{ref}} = A * (1 - S) + B \quad (16)$$

548 with $A=a/\rho_{ref}$ and $B = b/\rho_{ref}$, a and b being the values reported in Table 6.

549 Solutions are obtained from Equations 8 and 9 as:

$$550 \quad A = 3.317 * \ln(d_c) + 16 \quad (17)$$

$$551 \quad b = 0.1455 * d_c + 1 \quad (18)$$

552 Considering Archie's law, Equation 16 becomes:

$$553 \quad \frac{\rho}{\rho_{ref}} = S^{-n} \phi^{-(m-m_{ref})} \quad (19)$$

554 where $n= 2.24$, m_{ref} corresponds to the value calculated in Section 3.1, $m_{ref} = 3.153$, and

555 values of m are given by Equation 10. We have:

$$556 \quad \frac{\rho}{\rho_{ref}} = (3.317 * \ln(d_c) + 16) * (1 - S) + (0.1455 * d_c + 1) \quad (20)$$

$$557 \quad \frac{\rho}{\rho_{ref}} = S^{-n} \phi^{-(m-m_{ref})} \quad (21)$$

558 where $m = 0.0389 * d_c + 3.153$ and d_c is the carbonation depth in mm

559

560 [If these laws are validated with concretes presenting other porosities, they may be used for](#)
561 [different concrete types if the \$\rho_{ref}\$ measurement is given.](#) This ρ_{ref} measurement value should
562 become a durability indicator on which the choice between concretes for engineering
563 structures could be based [\[Baroghel-Bouny, 2004\]](#).

564 These laws present equations with two unknown variables (saturation level and carbonation
565 depth) whereas the survey of the structure provides only the resistivity ρ . Consequently, it is
566 essential to combine this equation (linear or exponential) with the relationship established for
567 permeability.

568

569 4.3 Permeability analysis

570 In order to establish correlations that are independent of the permeability measured on dry,
571 non-carbonated concrete, a relative permeability approach is used [\[Djerbi Tegger 2013,](#)
572 [Kameche 2014\]](#). Permeability values are then processed after being dividing by the reference
573 value $K_{ref,T}$. This value, which is the average K value of the Torrent permeability measurements

574 on dry Slabs C1-1-8-N, C1-1-7-N, C1-1-1-T and C1-1-2-T, is $27.34 \cdot 10^{-16} \text{ m}^2$. The
575 permeability measured on a sound, dry sample should become a mandatory parameter for
576 selecting concrete mixtures. This value can be considered as an intrinsic transport property
577 since the impact of carbonation and pore saturation is canceled out. This measurement value
578 might become a durability indicator that could be provided with the formulation of concrete
579 [Baroghel-Bouny 2004, Aït-Mokhtar 2013].

580 The results are displayed in [Figures 16 through 19](#) for different carbonation depths. They are
581 fitted first with a linear law, then with a Van Genuchten law modified by Mualem [1976] and
582 used by [Kameche 2014] to represent relative permeability as a function of saturation level.

583 When fitting with the linear law, the coefficients of determination achieved using Equation 15
584 are obtained as:

$$585 \quad \frac{K}{K_{\text{ref,T}}} = e^{-0,0935 \cdot d_c} * (1 - S) \quad (22)$$

586 with d_c the carbonation depth in mm.

587 The modified Van Genuchten law (VG law) is then defined as:

$$588 \quad \frac{K}{K_{\text{ref,T}}} = (1 - S)^q * (1 - S^2) \quad (23)$$

589 Parameter q is determined by fitting this law with the experimental results obtained on non-
590 carbonated slabs. The results displayed in [Figure 16](#) show that $q = 0.89$. This value is lower
591 than the values previously achieved for cementitious materials. Monlouis-Bonnaire
592 [Monlouis-Bonnaire 2004] proposes $q = 5.5$ for cementitious materials and [Kameche 2014],
593 $q = 3.5$ for relative gas permeabilites measured using the Cembureau method. Permeability
594 variations are very pronounced when they are measured using the Torrent permeameter. For a
595 40% saturation level, relative permeability is 0.6 with the Torrent method but only 0.1 with
596 the Cembureau method [Kameche 2014]. Parameter q , used to quantify the effect of saturation
597 level on relative permeability, is held constant for carbonated slabs. However, a C factor is
598 introduced to consider the decrease in relative permeability with carbonation.

599

600 The VG law then becomes:

$$601 \quad \frac{K}{K_{ref,T}} = C * (1 - S)^q * (1 - S^2) \quad (24)$$

602 **Figure 20** presents the empirical parameter, C, determined by fitting with the experimental
 603 results.

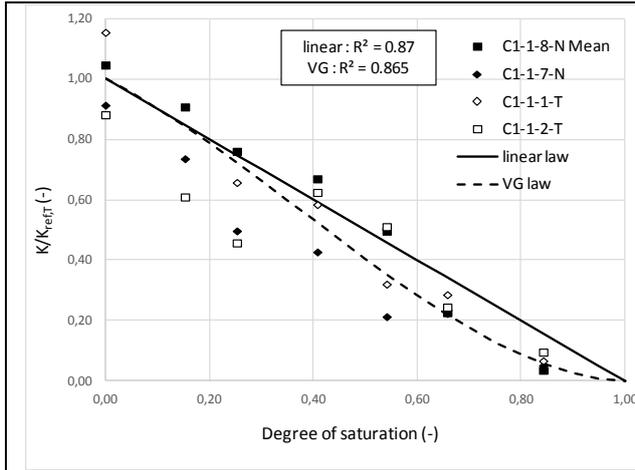


Figure 16: Relative permeability versus saturation degree for non-carbonated slabs

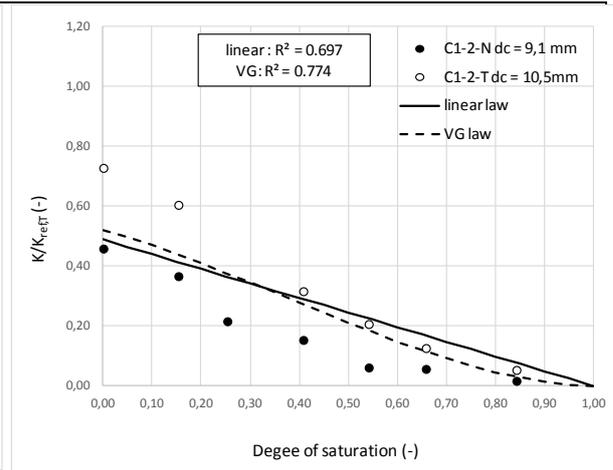


Figure 17: Relative permeability versus saturation degree for carbonated slabs C1-2-N et C1-2-T (d_c mean = 9.8 mm)

604

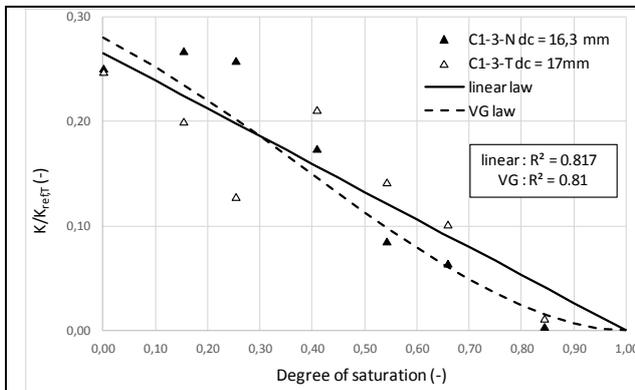


Figure 18: Relative permeability versus saturation degree for carbonated slabs C1-3-N et C1-3-T (d_c mean = 16.65 mm)

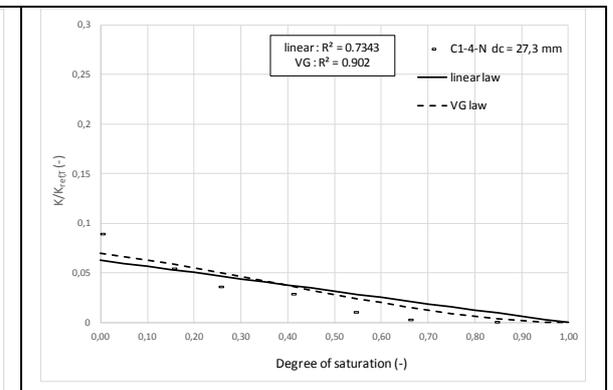


Figure 19: relative permeability versus saturation degree for carbonated slabs C1-4-N ($d_c = 27.3$ mm)

605

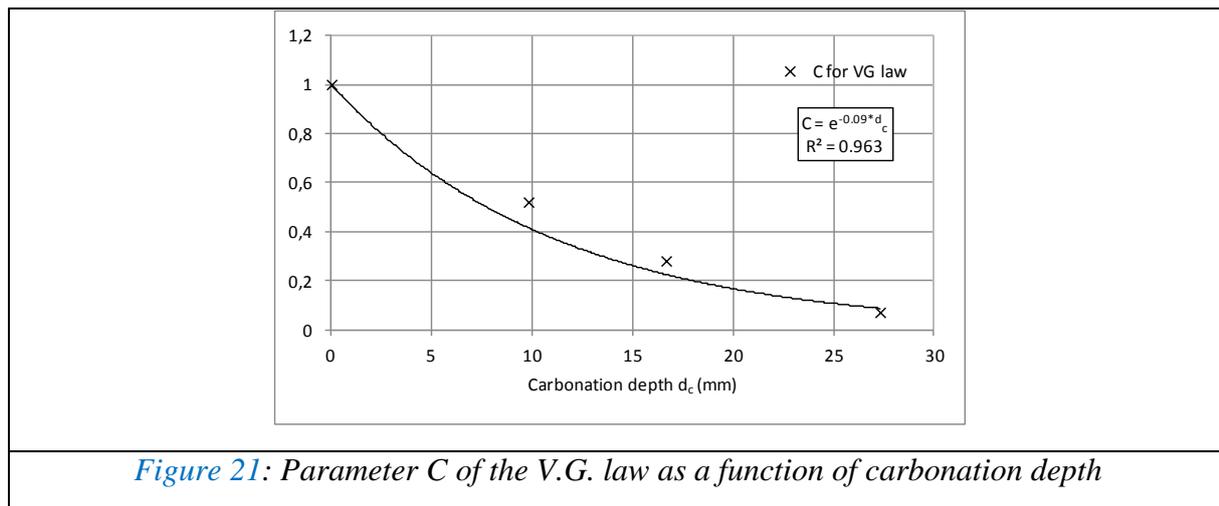


Figure 21: Parameter C of the V.G. law as a function of carbonation depth

606
 607 The coefficients of determination demonstrate that the VG law describes relative permeability
 608 evolution better. This law can therefore be used to describe Torrent permeability evolution
 609 according to carbonation depth and saturation level as:

610

$$611 \quad \frac{K}{K_{\text{ref},T}} = e^{-0.09*d_c} * (1 - S)^{0.89} * (1 - S^2) \quad (25)$$

612 with d_c the carbonation depth in mm.

613 The VG law for relative permeability and Archie's law for relative resistivity can be used to
 614 obtain better coefficients of determination than with linear laws, in particular for carbonated
 615 slabs. The two laws can be combined to determine the saturation level and the carbonation
 616 depth of similar concrete structures. However, in order to use both measurement techniques
 617 simultaneously, the concrete saturation level of the structure must fall within the range 40-
 618 66%.

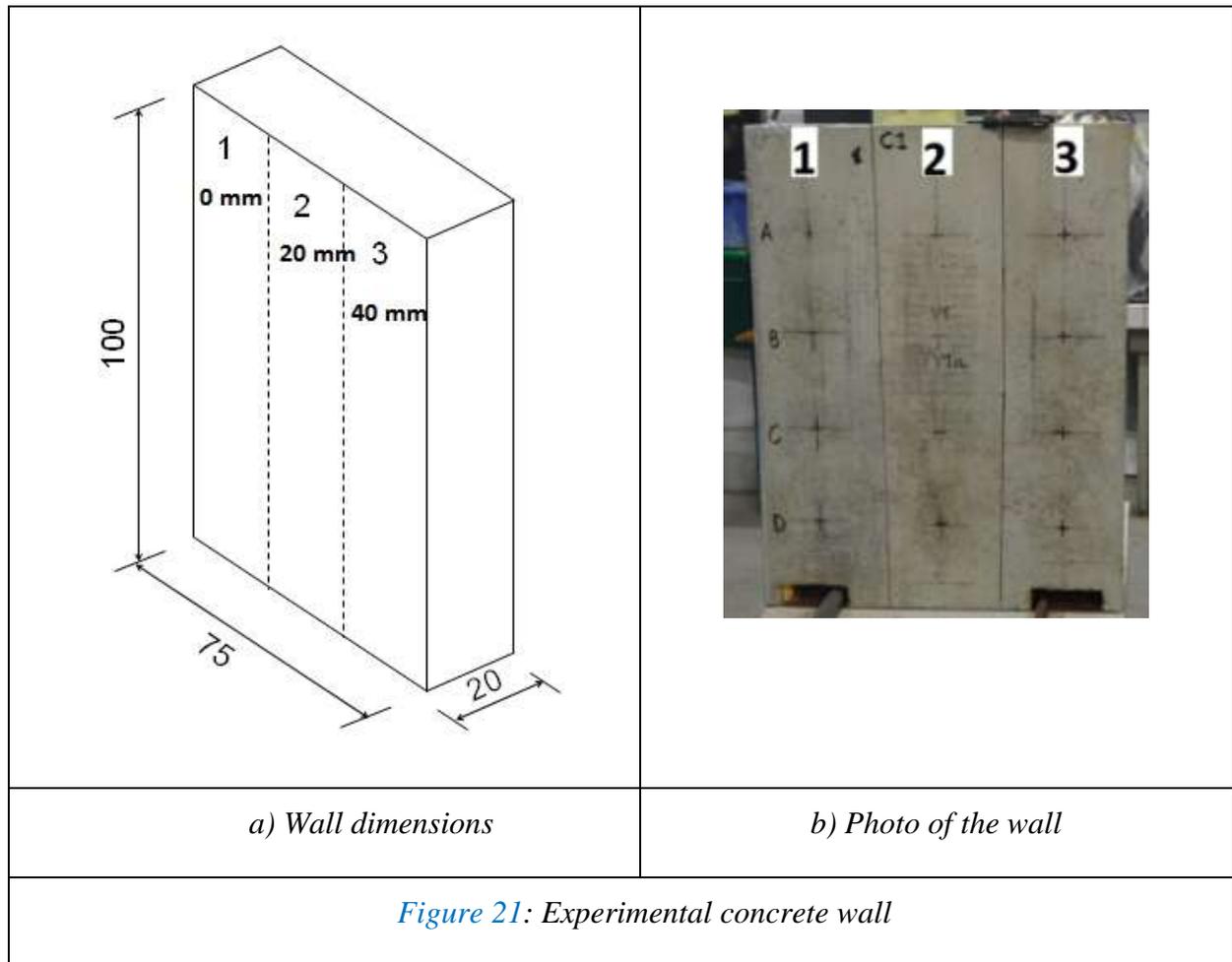
619 *If validated with concrete presenting other porosities, these laws may also be used on other*
 620 *concrete materials if $K_{\text{ref},T}$ measurements, carried out using the Torrent permeameter on dry*
 621 *non-carbonated samples, and ρ_{ref} measurements, carried out using the Wenner resistivimeter*
 622 *on saturated non-carbonated samples, are given. Both measurements could be performed prior*
 623 *to the construction in order to ensure the best choice of concrete formulations. During the*
 624 *survey conducted to apply these laws, the surveyed areas of the structure should be checked*

625 for cracking, as concrete damage modifies permeability [Picandet, 2001; Djerbi, 2008 and
626 2013] as well as resistivity measurements [Taillet, 2014; Lataste 2003]. If damage is detected,
627 another non-destructive technique should be used and relationships between, for instance,
628 resistivity measurement and saturation level, carbonation depth and damage should be
629 established.

630

631 4.4 Validation using a concrete wall

632 The slabs studied in this paper were used to examine the influence of carbonation on NDT
633 measurements by studying moisture homogeneity on saturated or partially saturated concrete.
634 Equations 11, 12 and 15 were established using experimental measurements carried out on the
635 slabs. In order to validate the performance of these laws, an experimental wall, 100 cm x 75
636 cm and 20 cm thick, was prepared (Figure 21a). The concrete used for the wall was the same
637 as for the slabs. A reinforcement mesh was placed at a depth of 25 mm on one face of the
638 wall. The diameter of the bars was 10 mm and the size of square mesh was 20 cm.
639 Measurements were only made on the non-reinforced side of the wall in order to avoid the
640 influence of the reinforcement, especially on resistivity measurements. This face of the wall
641 was divided into three vertical sections corresponding to different carbonation depths. After
642 28 days of storage in a humid chamber, the first section (noted 1 in Figure 21), corresponding
643 to a carbonation depth of 0 mm, was completely sealed. Then, the wall was placed in a
644 carbonation chamber at 20 °C and 65% relative humidity, with a CO₂ content of 50% to
645 accelerate the carbonation process. Section 2, corresponding to a carbonation depth of 20 mm,
646 was also sealed after the same exposure to the carbonation process as Slabs C1-3N and C1-
647 3T. The wall was finally removed from the carbonation chamber after the same exposure time
648 as Slab C1-4N.



649

650 NDT measurements were carried out at twelve points on the wall (indicated with crosses in
651 [Figure 21b](#)). Then, core samples were taken in the center of each mesh to obtain real
652 carbonation depths and saturation levels. Each core sample was cut into three pieces: one
653 from each end, with a thickness corresponding to the desired carbonated depth, and one
654 middle piece corresponding to sound concrete (non-carbonated). [Because coring and sawing](#)
655 [were done under water, at the end of the operations, samples were dried with a cloth to avoid](#)
656 [the absorption of water as far as possible and so to avoid modifying the moisture content.](#) The
657 carbonation depth was observed by spraying the core samples with the phenolphthalein color
658 indicator and the saturation level was calculated after drying the core samples as described in
659 Section 2.3. The values reported in Table 7 are the mean values obtained from 8

660 measurements (four core samples for each vertical section and two pieces for each core
661 sample).

Vertical section	Measured carbonation depth (mm)	Measured saturation level (%)	Mean permeability 10^{-16} m^2	Mean Wenner resistivity $\Omega \cdot \text{m}$	Calculated carbonation depth (mm)		Calculated saturation level (%)	
					equations 11 + 15	equations 12 + 15	equations 11 + 15	equations 12 + 15
1	0.25	65	1.7	22	0.003	0	93.7	93.7
2	18.9	58.9	1.07	407	24.4	24.38	61.7	61.8
3	33.1	60.6	0.101	504	48.8	38.9	64.9	86

662 *Table 7: Comparison between measured and calculated values of carbonation depth and*
663 *saturation level.*

664
665 In Section 1, Torrent permeability measurements were carried out with a saturation level that
666 was considered high for such a measuring technique. As shown in [Figure 14](#), CoV increased
667 with the degree of saturation. This can explain the high calculated degree of saturation
668 obtained in Section 1 in both cases (Equations 11+15 and 12+15). As regards the carbonated
669 sections, the calculated values for carbonation depth were [overestimated](#) by non-destructive
670 testing, which provides a safety margin regarding the service life assessment of concrete
671 structures but can be expensive for owners because repair will take place earlier. The
672 combination of Equations 12 and 15 is more consistent with the measured data especially as
673 regards carbonation depth. This combination is recommended for carbonation depth
674 calculations, while the combination of Equations 11 and 15 is advised for calculating the
675 saturation level after testing concrete structures using the Wenner resistivimeter and the
676 Torrent permeameter.

677
678 **5 Conclusion**

679 In this study, resistivity and permeability measurements were performed on carbonated slabs
680 conditioned at different saturation degrees. The results confirm that resistivity and
681 permeability are both very sensitive to concrete moisture. They also clearly show that

682 carbonation affects resistivity and permeability. The higher the carbonated depth is, the higher
683 is the resistivity and the lower is the permeability. This can be related to the reaction of
684 carbonation, which decreases porosity. Resistivity cannot be assessed for water saturation
685 degrees of less than 40% because, at such low moisture content, the continuity of the
686 interstitial solution vanishes and the electrical current cannot circulate. On the other hand,
687 permeability cannot be measured for saturation degrees higher than 83% due to the
688 obstruction of pores by the interstitial solution, which prevents gas penetration. An analysis of
689 the test results has shown a coefficient of variation of 20% for resistivity and less than 30%
690 for permeability, which increases with the increase of saturation degree whatever the
691 carbonated depth.

692 Two empirical laws have been proposed here to model resistivity measurements versus
693 carbonated depth and saturation degree. The first one is adapted from a linear law between
694 resistivity and saturation degree to take the carbonated depth into account. For the second one,
695 Archie's law is adapted to take carbonation into account. The coefficient of determination is
696 better for the linear model, which is easier to determine. In the same way, a linear model
697 between permeability coefficient and saturation degree is extended to take the carbonated
698 depth into account with a good determination coefficient.

699 Models involving relative resistivity and relative permeability have also been proposed. For
700 resistivity, both the linear and Archie's law are considered. For permeability modeling, a
701 modified Van Genuchten law seems more efficient than the modified linear model. [It would
702 be interesting to check these models with concrete presenting other porosities.](#)

703 Finally, the different models have been used to predict both saturation degree and carbonated
704 depth on a wall made with the same concrete as the slabs. The results show that the models
705 are able to distinguish different carbonated depths but the assessment precision needs to be
706 improved. Additional research is required, in particular to take the presence of cracks into

707 consideration. These may due to shrinkage or to mechanical effects, for instance, which have
708 a significant influence on measurements. In order to improve the quality of the investigation,
709 a third technique could be proposed, such as ultrasonic surface waves, which are able to
710 investigate the cover concrete.

711

712

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716 [Becker, a native English speaker, commissioned to proofread the final English version of this](#)
717 [paper.](#)

718

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