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1 **An alternative method to measure corrosion rate of reinforced concrete** 2 **structures**

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7

8 **Abstract**

9 A new probe, which does not use a confinement ring, has been developed to assess the
10 corrosion state of reinforced concrete structures. Galvanostatic polarization is
11 performed and the rebar corrosion potential, concrete resistivity and rebar corrosion rate
12 are evaluated using an iterative calculation algorithm. The surface linear polarization
13 resistance ($R_{P,s} = \Delta E_P / j_{PI}$) of the rebar / concrete interface is calculated by converting the
14 potential measured at the surface into the rebar polarization ΔE_P and the current density
15 at the point of interest (PI) j_{PI} using 3D numerical simulations. The calculation involves
16 three geometrical parameters that modify the current and potential distribution in the
17 concrete: the rebar spacing, s ; the concrete cover, c ; and the rebar diameter, D . Concrete
18 cover resistivity is calculated using the instantaneous ohmic drop measured at the
19 beginning of the galvanostatic polarization and the rebar corrosion rate is calculated
20 using the steady-state potential. As the rebar corrosion rate also modifies the potential
21 distribution in concrete, an iterative methodology was developed, using different
22 supposed corrosion rates. Finally, the probe and associated methodology were used to
23 evaluate the corrosion state of eight concrete slabs. Half of them were prepared with
24 chloride in order to initiate corrosion. Four slabs were stored outdoors, two indoors in
25 an ordinary laboratory environment and two indoors in a 50% CO₂ gas chamber. The
26 three corrosion parameters evaluated (corrosion potential, concrete cover resistivity and
27 rebar corrosion rate) were in good agreement with the composition of the slabs and their
28 curing conditions.

29 **Highlights**

- 30 • A new probe to assess corrosion rate of reinforced concrete structure was
31 developed

32 • The linear polarization resistance $R_{p,s}$ is calculated using 3D numerical
33 simulations

34 • Rebar spacing, concrete cover and resistivity modify the potential distribution

35 **Keywords**

36 Corrosion rate, reinforced concrete structure, surface linear polarization resistance (SLPR),
37 3D numerical simulation, point of interest (PI), iterative methodology.

38

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46 Alpha RLH.

47

48 **1 Introduction**

49 Steel corrosion is the main cause of deterioration in reinforced concrete structures and the
50 high cost of repairs is responsible for considerable financial losses [1,2]. Corrosion detection
51 and the evaluation of its kinetics could optimize the maintenance of such structures and
52 increase users' safety.

53 A passive layer formed in the high pH of the surrounding concrete initially protects steel
54 rebars from corroding. However, under certain conditions, this protective layer can be locally
55 (macro-cell corrosion) or totally (uniform corrosion) destroyed. Macro-cell corrosion is
56 usually caused by local chloride ingress from the external environment (de-icing salts or
57 marine environment) while uniform corrosion results from the penetration of CO₂ from the
58 atmosphere (concrete carbonation) [3], although coupling with passive armatures can lead to
59 macro-cell currents. The theory developed in this article assumes uniform corrosion.

60 Different physical parameters are relevant to assess the corrosion state of a reinforced
61 concrete structure: half-cell corrosion potential, E_{corr} ; concrete resistivity, ρ ; or rebar corrosion
62 rate, i_{corr} . Corrosion potential measurement evaluates the risk of corrosion [4]. Concrete cover
63 resistivity is increasingly being considered as a durability index for assessing the long-term
64 performance of concrete structures [2-4]. Such resistivity can be measured by the device
65 presented in this article and details of the measurement principle are to be found in [8]. It is
66 usually considered that concrete resistivity and corrosion rate are inversely proportional
67 [9,10]. However, in an extensive review article, Horbostel et al. [11] demonstrated that the
68 relation established cannot be unique as it depends on several parameters. This explains the
69 growing interest of assessing corrosion by more quantified techniques than the corrosion
70 potential or resistivity measurements and has led to several publications dealing with
71 corrosion rate [1,2,12–16]. The corrosion rate of steel plays an important role in safety
72 evaluations, maintenance decisions and residual life predictions for the existing RC structures

73 [13]. The rebar corrosion rate, i_{corr} , depends on the binder composition, moisture content,
 74 concrete resistivity, pore solution pH, temperature, and dissolved oxygen concentration
 75 [14,17–21], all of which can evolve with time, depending on the concrete exposure
 76 conditions.

77 Most of the time, corrosion rate, which can also be called corrosion current density, is
 78 estimated by determining the linear polarization resistance R_P (LPR). Polarization is a
 79 transient phenomenon. In the steady state, the relation between the rebar polarization, ΔE_P
 80 ($\Delta E_P = E - E_{corr}$ [V]), and the current density, i [$A.m^{-2}$], flowing through the interface is
 81 governed by the non-linear Butler-Volmer equation:

$$i = i_{corr} \left(e^{\ln(10) \frac{E - E_{corr}}{b_a}} - e^{\ln(10) \frac{E - E_{corr}}{b_c}} \right) \quad \text{Eq. 1}$$

82 where i_{corr} [$A.m^{-2}$] is the corrosion rate, and b_a and b_c [V] are the Tafel slopes [22]. The LPR
 83 is the ratio of a small rebar polarization, ΔE_P , to the current flowing through the concrete /
 84 steel interface in the steady state. It is generally considered that a maximum rebar polarization
 85 ΔE_P of 20 mV enables the curve to stay on the linear part of the Butler-Volmer equation and
 86 guarantees the reversibility of the measurement. Stern and Geary [23] proposed an empirical
 87 relation between corrosion rate and the LPR R_P [Ω] :

$$i_{corr} = \frac{B}{R_P A} \quad \text{Eq. 2}$$

88 where surface area A is taken to be the uniformly polarized area of the steel. This equation
 89 can only be used for uniform corrosion. B is a proportionality constant. It depends on the
 90 anodic and cathodic Tafel slopes, b_a and b_c respectively:

$$B = \frac{b_a b_c}{\ln(10)(b_a + b_c)} \quad \text{Eq. 3}$$

91 Usually, B is assumed to be 26 mV for passive rebars and 52 mV for active ones [16].
 92 However, as far as we know, these parameters cannot be measured on site with non-

93 destructive tests and large variations of these parameters have been demonstrated with Tafel
94 analysis on cylinders [24–26].

95 Various methods exist to determine the LPR on site: galvanostatic [27], potentiodynamic
96 [27,28], coulostatic [29] or CEPRA methods [15]. Most of the time, on site, the LPR is
97 measured according to the RILEM TC 154-EMC [16] recommendations in which a
98 confinement ring is employed. However, this method is based on two strong hypotheses that
99 do not hold true on site. First, the rebar is assumed to be uniformly polarized. Several studies,
100 usually based on numerical simulation, have proved that this is not the case. The point of the
101 rebar right under the polarizing probe is the most polarized [30–33]. In the present study, this
102 point will be referred to as the point of interest (PI).

103 Commercial devices are usually used to determine the polarization resistance. They are based
104 on a confinement technique (a guard ring) in order to control the polarized area and confine
105 the current to a well-defined area A (see Eq. 2) of the steel rebar [12]. In a recent study,
106 Fahim et al. [15] compared two devices and showed that they were not able to calculate the
107 corrosion rate for the passive state, while satisfactory results were obtained for the active
108 state. Other investigations have revealed that different corrosion rates are obtained when these
109 commercial devices are used [34–37]. The main reason for the discrepancies is attributed to
110 confinement problems [38,39]. Nygaard et al. [34] developed a quantitative method to assess
111 confinement techniques, which indicated that, for a passive rebar, the actual corrosion rate
112 calculated by a commercial device was approximately 10 times too high, while it was 100
113 times too high for another device because these instruments were not able to confine current.
114 Thus, a new solution is needed.

115 This work was carried out as part of the DIAMOND project [40], which aims to create a new
116 electrochemical device to assess the corrosion state of reinforced concrete structures by
117 measuring half-cell corrosion potential, concrete resistivity and corrosion rate simultaneously

118 with the same device. The probe geometry is simpler as no guard ring is employed. The
119 corrosion rate calculation is based on three-dimensional numerical simulations that take
120 several geometrical parameters into account (concrete cover and resistivity, rebar diameter
121 and spacing). In addition, an iterative method is developed to evaluate the corrosion rate as
122 this parameter also modifies the distribution of current lines in the system.

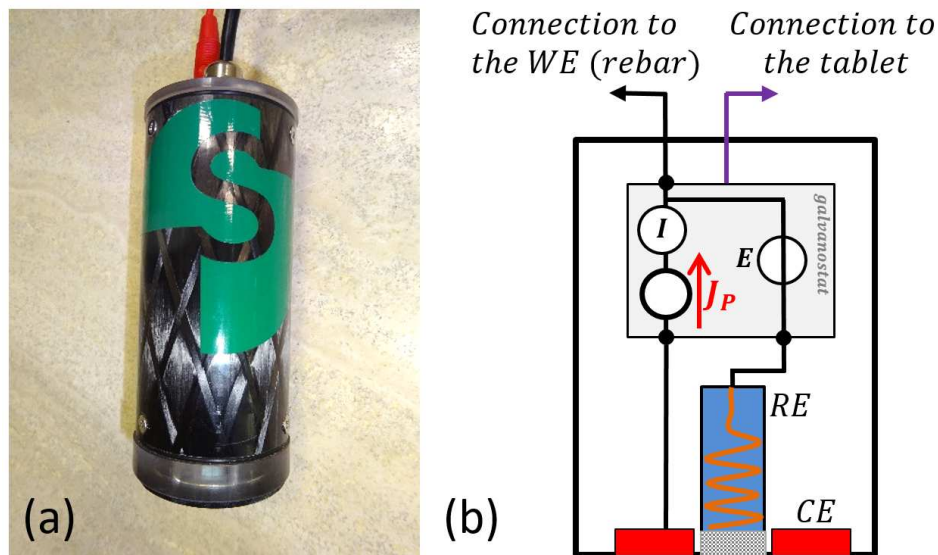
123 The present study focusses on corrosion rate assessment. The concrete cover resistivity
124 measurement method was described in detail in [8]. Here the DIAMOND probe for on-site
125 measurements will be presented first and will be used to identify the corrosion state of rebars
126 embedded in concrete slabs that are presented later. The measurement methodology will then
127 be introduced, with numerical modelling of the measurement using COMSOL software and
128 presentation of the numerical results. Finally, the experimental results will be presented and
129 discussed.

130 **2 Materials**

131 *2.1 DIAMOND probe characteristics*

132 Figure 1 (a) shows a picture of the DIAMOND probe and a schematic layout is given in
133 Figure 1 (b). The DIAMOND probe consists of a cylindrical probe in which a galvanostat is
134 inserted (unlike the previous prototype probe presented in [8], where an external galvanostat
135 was used for measurements). The cylinder is 50 mm in diameter and 130 mm high and weighs
136 182 grams. The measuring device was designed with reduced size and load in order to
137 facilitate on site measurements. The Counter Electrode (CE) is a 22 mm diameter disk of 1
138 mm diameter silver wire wrapped in a spiral around a central space where the 5 mm diameter.
139 Reference Electrode (RE) is placed in order to register the potential on the concrete surface.
140 The electrical continuity between the RE and the concrete surface is provided by a non-shrink
141 mortar stuck on the CE and a 1 mm thick sponge in contact with the concrete surface. To

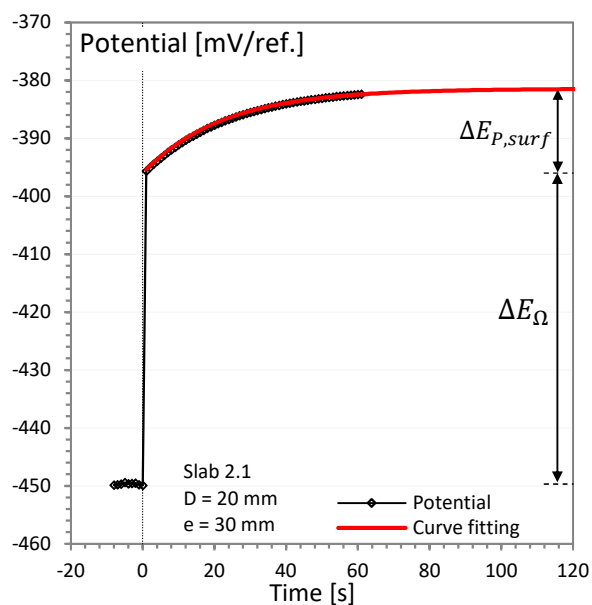
142 perform the measurement, the probe is then electrically connected to the reinforcement
143 network that constitutes the working electrode (WE).
144 The probe is linked to a portable tablet with a software developed by the authors on Excel.
145 The software controls the test, provides the signal required for polarization and registers the
146 potential on the RE. After the end of the test, the potential values measured on the RE are
147 automatically used to calculate the concrete cover resistivity and the rebar corrosion rate. The
148 concrete cover resistivity calculation was detailed in [8] and the corrosion rate evaluation
149 method is detailed in this article (part 5).



150
151 **Figure 1. DIAMOND probe: side view (a), schematic layout (b).**

152 A typical polarization curve recorded during on-site measurement is presented in Figure 2.
153 Before the polarization, a galvanostatic pulse current of $10 \mu\text{A}$ is applied. Depending on the
154 response, the galvanostatic current (from 1 to $25 \mu\text{A}$) is automatically calculated for the
155 transient polarization. The galvanostatic polarization is then applied. If the potential measured
156 is not stabilized (less than 0.1 mV of variation during 20 seconds) after 60 seconds (which is
157 always the case for passive rebar) curve fitting is performed using a typical exponential
158 charging RC circuit (Randles model) and the potential is estimated at 300 seconds [41]. The
159 data recorded are then converted into the output data of interest to quantify the corrosion state

160 of the reinforced concrete structure under inspection: corrosion potential, concrete cover
 161 resistivity and corrosion rate of the rebar. The instantaneous ohmic drop is converted into
 162 concrete cover resistivity as presented in [8] and the steady-state response is used to
 163 determine the rebar corrosion rate. This conversion process is based on graphs obtained with
 164 numerical simulation and will be presented later (in part 5). The conversion requires the rebar
 165 diameter, concrete cover and rebar spacing to be manually entered in the software as they are
 166 used in the numerical simulation.



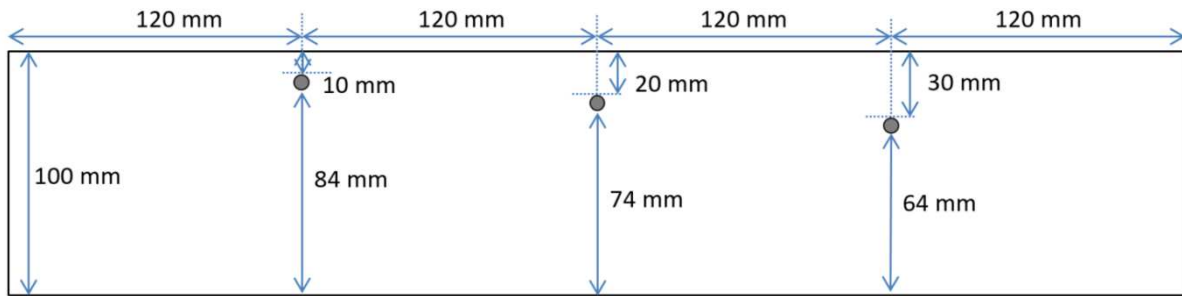
167

168 **Figure 2. Typical polarization curve measured on-site by the probe.**

169 **2.2 Concrete slabs for experimental measurements**

170 The probe and the developed method were used to evaluate the corrosion state of rebars
 171 embedded in various slabs. The slabs, 100 x 240 x 480 mm³, were prepared using CEM I
 172 cement and a very high water/cement ratio of 1.05 in order to promote fast moisture balancing
 173 in the material. Half of the slabs were prepared with 5% NaCl (of the cement mass) in order
 174 to avoid the initiation phase of corrosion and to start immediately the propagation phase. Each
 175 slab contained three similar rebars placed at concrete cover depths of 10, 20 and 30 mm. Slabs
 176 can also be returned which enable to investigate three other concrete covers (i.e. 64, 74 and 84

177 mm as seen in Figure 3 for a rebar diameter of 10 mm). Two rebar diameters, 6 and 20 mm,
178 were employed. Six polymer heat shrink tubes were placed on each slab where the rebars
179 came out, so as to prevent water ingress and corrosion along the rebar from outside. A picture
180 of a slab is presented in Figure 4.



181

182 **Figure 3. Side view of the slabs prepared with 6 mm diameter rebar.**



183

184 **Figure 4. Picture of a slab (D = 6 mm - slab placed outdoors).**

185 All the samples were cured for 28 days under wet conditions (20°C, 95% RH). Then, four
186 different curing conditions were applied for six months before the measurements started:

- 187
- 188 - Cure 1: Slabs outdoors, no chloride
 - 189 - Cure 2: Slabs outdoors, with chloride
 - 190 - Cure 3: Indoors, no chloride, placed in a 50% CO₂ carbonation chamber with around
191 65% RH
 - 192 - Cure 4: Indoors, with chloride. Temperature 20°C, relative humidity not controlled

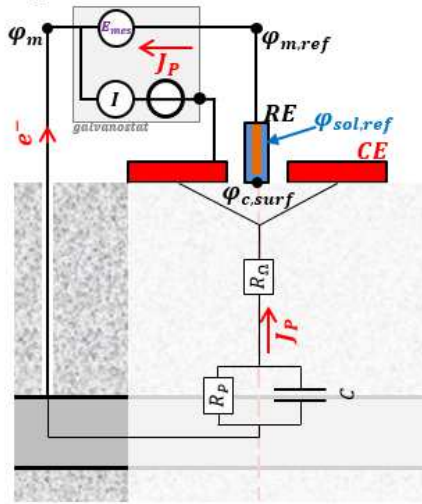
192 For each type of curing conditions, one slab was prepared with three 6 mm diameter rebars
193 and a second slab was prepared with three 20 mm diameter rebars. The slabs placed outdoors
194 were stored at LMDC Toulouse (France). The aim of this article is not to investigate the
195 influence of these different curing conditions on the concrete properties but to create various
196 extreme cases leading to different corrosion states.

197 **3 Methodology**

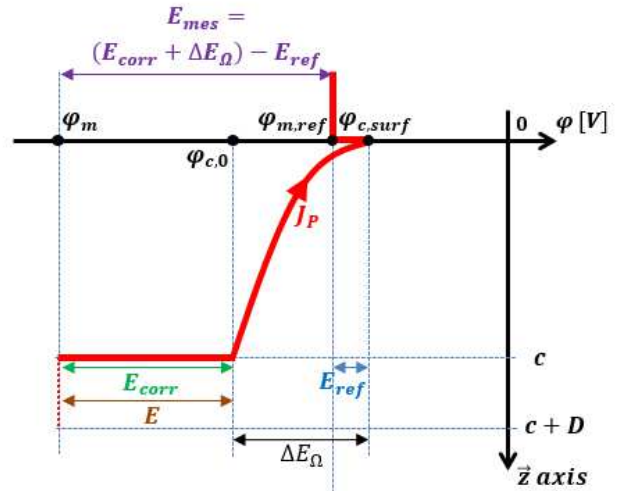
198 The schematic layout of the probe and the three steps of the polarization process are detailed
199 in Figure 5. An electrical connection to the rebar must be made. The rebar diameter D [m] and
200 cover thickness c [m] can be measured when the electrical connection is set up or evaluated
201 by non-destructive techniques [42].

202 An equivalent electrical circuit is presented in Figure 5 (a). The concrete can be electrically
203 modelled by a resistance R_{Ω} . The rebar / concrete interface is modelled by a Randles model
204 associating a capacitance C and the LPR R_P in parallel. Note that this electrical circuit is a
205 simplified representation of the 3D problem. In order to visualize the three steps of the
206 measurement, several absolute potentials, φ , are introduced in the four parts of Figure 5.
207 These absolute potentials cannot be measured; only measurement of the difference between
208 two absolute potentials is possible. The reference potential E_{ref} of the RE is the difference
209 between the absolute potential $\varphi_{\text{m,ref}}$ of the metal used in the probe (Cu) and its surrounding
210 solution $\varphi_{\text{sol,ref}}$ (CuSO_4).

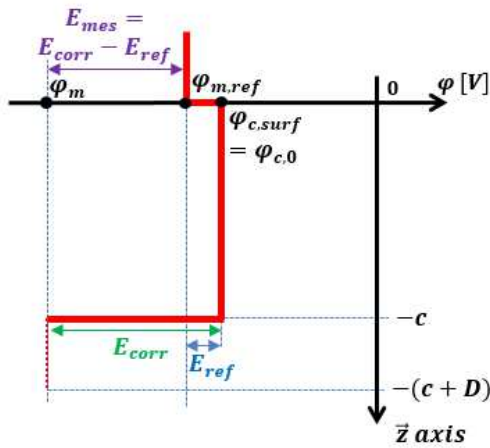
a. Equivalent electrical circuit



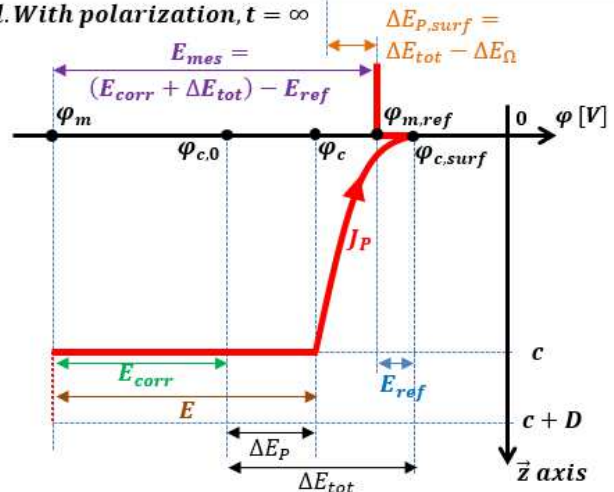
c. With polarization, $t = 0$



b. Without polarization



d. With polarization, $t = \infty$



211

212

Figure 5. Equivalent electrical circuit (a). Absolute potential evolution without

213

polarization (b), with polarization, $t = 0$ (c), and with polarization, $t = \infty$ (d).

214

The electrical continuity between the concrete surface and the surrounding solution of the

215

probe is obtained with a mortar without shrinkage stuck on the CE and a 1 mm thick sponge.

216

The absolute potential in the surrounding solution of the RE $\varphi_{sol,ref}$ is then equal to the

217

absolute potential of the concrete in the surface $\varphi_{c,surf}$ as there is no significant resistance

218

between these two media.

219

The corrosion potential E_{corr} (half-cell rebar / concrete) is the difference between the

220

surrounding concrete absolute potential without polarization, $\varphi_{c,0}$, and the metal rebar absolute

221

potential, φ_m .

222 The electrical potential evolution along the vertical, \vec{z} axis is presented in the last three parts
223 of Figure 5. The \vec{z} axis is defined as the axis passing through the centre of the probe on the
224 surface and the PI. It is represented in red in Figure 6. Without any polarization, the potential
225 measured by the RE is the difference between the corrosion potential, E_{corr} , and the reference
226 potential, E_{ref} , (Figure 5 (b)).

227 When the galvanostatic current is applied (Figure 5 (c)), the potential of the rebar / concrete
228 interface remains equal to the corrosion potential as the capacitance of the Randles model is
229 short-circuited. The instantaneous ohmic drop, ΔE_{Ω} , measured by the RE is due only to the
230 concrete resistance, R_{Ω} . A previous study exploited this ohmic drop to determine the concrete
231 cover resistivity. It was shown that the ohmic drop measured depended on the concrete
232 resistivity and cover and also on the rebar diameter. It was also demonstrated that the rebar
233 spacing had no significant influence.

234 The schematic layout of the potential of the system, in the steady state, is presented in Figure
235 5 (d). At steady state, the capacitance acts as an infinite resistance. The potential in the rebar /
236 concrete interface is no longer equal to the corrosion potential. The polarization of the rebar,
237 $\Delta E_{\text{P}} = E - E_{\text{corr}}$, is different from zero. The relation between the current flowing through the
238 interface and its polarization is governed by the Butler-Volmer equation (Eq. 1). In the steady
239 state, the rebar polarization reaches its maximum value, ΔE_{P} . The difference between the
240 potential measured on the surface, ΔE_{tot} , and the instantaneous ohmic drop, ΔE_{Ω} , is the
241 polarization measured on the surface, $\Delta E_{\text{P,surf}}$, and it is not equal to the rebar polarization ΔE_{P}
242 because of the 3D nature of the problem (Figure 5 (d)).

243 The potential measured on the surface is influenced by both the concrete resistance R_{Ω} and
244 the rebar / concrete interface LPR R_{P} . As demonstrated for the instantaneous ohmic drop, the
245 steady-state response will also depend on the geometrical parameters of the study, the
246 concrete cover, the rebar diameter and the concrete resistivity. Moreover, rebar spacing will

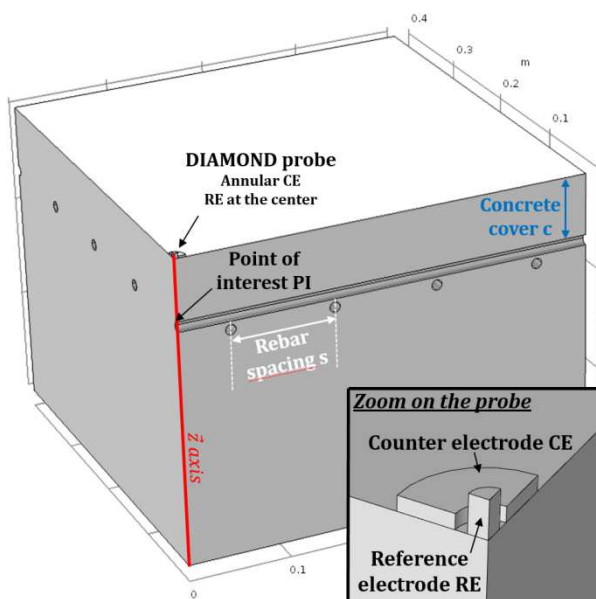
247 also influence the rebar polarization at the PI. The 3D numerical model developed on Comsol
248 will be used below to convert the data measured on the surface, after the instantaneous ohmic
249 drop and at steady-state, to determine the rebar corrosion rate, i_{corr} .

250 4 Finite element model

251 The two steps of the polarization (instantaneous ohmic drop - Figure 5 (c); steady state -
252 Figure 5 (d)) were modelled with Comsol Multiphysics finite element model software. The
253 AC/DC toolbox was used to evaluate current and potential distribution in the modelled
254 geometry. The transient phase of the polarization was not modelled.

255 4.1 Geometry

256 The geometry of the model is presented in Figure 6 for an example where the concrete cover,
257 c , is 60 mm, the rebar diameter is 10 mm and the rebar spacing is 100 mm. In all the
258 simulations, the concrete slab is 300 mm high and 800 mm wide. As the problem exhibits
259 double symmetry, only a quarter of the slab is modelled. The probe is placed at the centre of
260 the slab above the central rebar. The probe model is shown in greater detail in the corner of
261 Figure 6. The point directly under the probe, at the interface of the top face of the rebar, is the
262 PI.



263

264 **Figure 6. Modelling geometry. In this example $D = 10$ mm, $c = 60$ mm and $s = 100$ m.**

265 **Zoom on the modelled probe in the corner.**

266 The annular CE and the cylindrical RE are both modelled with a material having a high
267 electrical conductivity of 10^5 S/m. The current ($J_P = 10 \mu\text{A}$) is injected on the top face of the
268 CE. It is constant for all the numerical simulations presented in this article. The rebar
269 framework is modelled with regularly spaced, perpendicular hollow cylinders. The cylinders
270 are electrically connected. The central cylinder with the PI on its top face, right under the
271 probe, is always present while other cylinders can be added to model more or less dense rebar
272 frameworks by modifying the rebar spacing, s . Three geometrical parameters were modified
273 in the present study: rebar spacing, s ; concrete cover, c ; and rebar diameter, D . The different
274 values of the modelled geometry parameters are presented in Table 1. A wide range of these
275 geometrical parameters was modelled in order to consider all the configurations that can be
276 found on site. Setting the rebar diameter to infinity is equivalent to modelling a metal plate.
277 The infinity rebar spacing corresponds to a single rebar.

278 **Table 1. Variable parameters considered in the numerical simulations.**

Parameter	Symbol	Unit	Number of values	Values
Corrosion rate	i_{corr}	$\mu\text{A}/\text{cm}^2$	3	0.1, 0.5, 1
Concrete resistivity	ρ	$\Omega\cdot\text{m}$	17	20, 40, 60, 80, 100, 200, 300, 400, 500, 600, 800, 1000, 1500, 2000, 4000, 6000, 10000
Rebar spacing	s	mm	5	∞ , 250, 200, 150, 100
Concrete cover	c	mm	11	10, 15, 20, 25, 30, 35, 40, 50, 60, 80, 100
Rebar diameter	D	mm	10	6, 8, 10, 12, 14, 16, 20, 25, 32, ∞

279 **4.2 Constitutive law, boundary conditions, electrochemical parameters and mesh**
280 **size**

281 In the model, concrete is assumed to be a homogeneous and isotropic material having a
282 uniform electrical resistivity ρ [$\Omega\cdot\text{m}$]. The seventeen resistivity values modelled are presented
283 in the second line of Table 1. The relation between the electrical current density vector j
284 [A/m^2] and the potential E [V] is governed by Ohm's law:

$$j = -\frac{1}{\rho}\nabla E \quad \text{Eq. 1}$$

285 In the system, the amount of current flux entering an enclosed surface of a material is equal to
286 the amount of current leaving it (charge conservation):

$$\nabla \cdot j = 0 \quad \text{Eq. 2}$$

287
288 Two different boundary conditions are imposed on the concrete / rebar(s) interface(s) to
289 model the two steps of the polarization. The polarization was divided in two distinct steps
290 because the transient evolution of the potential was not required to calculate the concrete
291 cover resistivity and the rebar corrosion rate. The 3D geometry is complex and the model
292 involves a large number of variables meaning that it would have been impossible to model the
293 transient polarization due to huge computer calculation duration. To model the instantaneous
294 ohmic drop, a very small electric resistance (0.00001Ω) is imposed because the capacitance
295 of the Randles model (Figure 5 (a)) is short-circuited at that moment (Figure 5 (c)).

296 The Butler-Volmer equation (Eq. 1) is used to model the steady state response. Three of the
297 four parameters of the Butler-Volmer equation are constant throughout this study and are
298 presented in Table 2. The Tafel slopes cannot be measured on-site. Based on the chosen Tafel
299 slopes, the coefficient B of the Stern-Geary equation is equal to 38 mV here which is between
300 the usually assumed value of 26 mV for active state and 52 mV for passive state. The
301 corrosion potential E_{corr} value has no impact on any of the results presented below; it only
302 modifies the reference.

303 **Table 2. Butler-Volmer parameters used in this study.**

Parameter	Corrosion potential	Anodic Tafel slope	Cathodic Tafel slope
Symbol	E_{corr}	b_A	b_C
Value	- 0.42 V	0.3 V/dec	0.125 V/dec

304

305 The aim of this article is to determine the rebar corrosion rate, i_{corr} , with non-destructive tests
 306 by using 3D numerical simulations to convert the data measured on the surface into the
 307 corrosion rate. However, running the numerical model requires the corrosion rate, i_{corr} , to be
 308 specified in the Butler-Volmer equation. This explains why an iterative approach is
 309 developed. Three corrosion rates, 0.1, 0.5 and $1 \mu\text{A}/\text{cm}^2$, are implemented in the Butler-
 310 Volmer equation at the rebar / concrete interface. These three corrosion rate values
 311 correspond to the upper transition value of negligible, low and moderate corrosion levels,
 312 respectively [16]. A current density higher than $1 \mu\text{A}/\text{cm}^2$ is considered as a high level of
 313 corrosion. The iterative automatic treatment of the measured data will be presented in part 5.5
 314 (Iterative measurement procedure).

315 All the other boundaries of the model are electrically isolated (no-flux boundary). The
 316 simulations were performed for all the combinations of the parameters presented in Table 1,
 317 corresponding to 25806 different cases. The different cases were modelled for the two steps
 318 of the polarization.

319 Tetrahedral linear elements were used. Mesh refinement was performed on the probe and the
 320 top parts of rebars. Several mesh refinement steps were applied until the potential was stable,
 321 for all the modelled configurations.

322 **5 Numerical results**

323 The simulation is used to determine the surface linear polarization SLPR [$\Omega \cdot m^2$] which is the
 324 ratio between the rebar polarization and the current density at the PI:

$$R_{P,S} = \frac{\Delta E_P}{j_{PI}} \quad \text{Eq. 4}$$

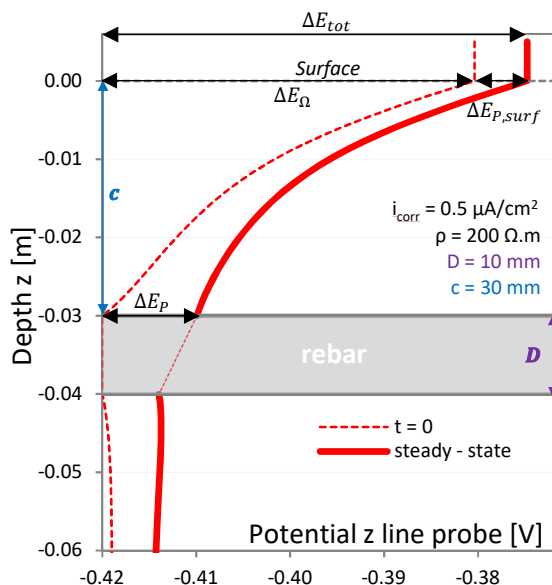
325
 326 The corrosion rate calculation is different from that of the majority of other studies, where a
 327 polarization process is used. Most of the time, the LPR [Ω] is calculated as the ratio between
 328 the rebar polarization and the current. The assumed polarized area, A , is then used to
 329 determine the rebar corrosion rate (see Eq. 2). In this study, the corrosion rate is deduced from
 330 the SLPR without using an assumed polarization area:

$$i_{corr} = \frac{B}{R_{P,S}} \quad \text{Eq. 5}$$

332 **5.1 Example of a potential evolution**

333 Figure 7 presents an example ($D = 10 \text{ mm}$, $c = 30 \text{ mm}$ and $\rho = 200 \Omega \cdot m$) of the evolution of
 334 the potential along the vertical \vec{z} axis (see Figure 6) obtained with Comsol Multiphysics. The
 335 dotted line represents the potential evolution at $t = 0$ (rebar is short-circuited) while the
 336 continuous line represents the steady state (Butler-Volmer equation for $i_{corr} = 0.5 \mu A/cm^2$).
 337 Once the galvanostatic current is applied, an instantaneous ohmic drop ΔE_Ω is observed on the

338 surface. At this moment, the rebar is short-circuited, which explains why the potential on the rebar interface remains equal to the corrosion potential ($E_{corr} = -0.42 \text{ V}$ in this example, see Table 2).



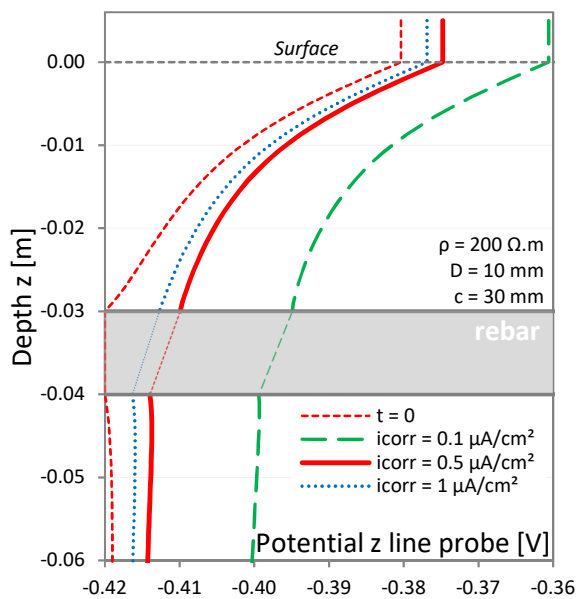
344

345 **Figure 7. Potential evolution along the \vec{z} axis at $t = 0$ (dotted line) and at steady state**
346 **(continuous line) for $i_{\text{corr}} = 0.5 \mu\text{A}/\text{cm}^2$, $D = 10 \text{ mm}$, $c = 30 \text{ mm}$ and $\rho = 200 \Omega\cdot\text{m}$.**

347 At steady state, the rebar is polarized ($\Delta E_P \neq 0$). The difference between the potential
348 measured on the surface ΔE_{tot} and the ohmic drop ΔE_{Ω} is called the polarization measured on
349 the surface $\Delta E_{P,\text{surf}}$. Due to the three-dimensional nature of the problem, the polarization
350 $\Delta E_{P,\text{surf}}$ is not equal to the rebar polarization ($\Delta E_P \neq \Delta E_{\text{tot}} - \Delta E_{\Omega}$). This explains the necessity
351 for a 3D numerical simulation: the rebar polarization cannot be directly determined from the
352 polarization measured on the surface as the relation between these two potentials depends on
353 several parameters.

354 5.2 Influence of the supposed corrosion rate i_{corr}

355 The previous example was presented for a current density of $0.5 \mu\text{A}/\text{cm}^2$. However, a
356 different current and potential distribution is expected if the rebar corrosion rate, i_{corr} is
357 modified. To illustrate this, Figure 8 is plotted for two additional corrosion rates, 0.1 and 1
358 $\mu\text{A}/\text{cm}^2$, while all the other parameters remain unchanged.

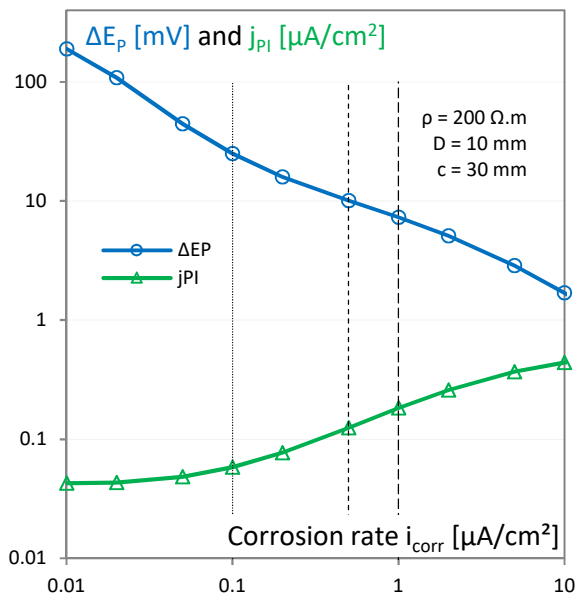


359

360 **Figure 8. Potential evolution along the \vec{z} axis at $t = 0$ (dotted line) and in steady state**
 361 **(continuous line) for $i_{\text{corr}} = 0.5 \mu\text{A}/\text{cm}^2$, ($D = 10 \text{ mm}$, $c = 30 \text{ mm}$ and $\rho = 200 \Omega\cdot\text{m}$).**

362 Figure 8 clearly shows that the potential measured on the surface, $\Delta E_{\text{P,surf}}$, and the rebar
 363 potential, ΔE_{P} , are significantly influenced by the rebar corrosion rate, i_{corr} . When the rebar
 364 corrosion rate decreases, the SLPR (and the LPR) increases, which explains the higher
 365 potential measured on the surface in the steady state. To determine the SLPR, both rebar
 366 polarization ΔE_{P} and j_{PI} are required.

367 In order to visualize the influence of the corrosion rate i_{corr} on both rebar polarization and
 368 current density at the PI, Figure 9 is plotted for a wide range of corrosion rates, i_{corr} , from 0.01
 369 to $10 \mu\text{A}/\text{cm}^2$ and for the same parameters as in Figure 7 and Figure 8 ($D = 10 \text{ mm}$, $c = 30$
 370 mm and $\rho = 200 \Omega\cdot\text{m}$).



371
 372 **Figure 9. Rebar polarization ΔE_{P} (circles) and current density at the PI j_{PI} (triangles)**
 373 **depending on the corrosion rate, i_{corr} . ($D = 10 \text{ mm}$, $c = 30 \text{ mm}$ and $\rho = 200 \Omega\cdot\text{m}$).**

374 The three corrosion rates i_{corr} used for the numerical simulations (i.e. 0.1, 0.5 and $1 \mu\text{A}/\text{cm}^2$)
 375 are represented with dotted black vertical lines. As highlighted in Figure 8, the rebar
 376 polarization, ΔE_{P} , increases when the corrosion rate is numerically decreased. In contrast, the

377 current density at the PI increases with corrosion rate because SLPR reduction enables more
378 current to flow through the interface right under the probe.

379 Thus, Figure 8 and Figure 9 enable us to understand that the current distribution is not only
380 influenced by the concrete resistivity and geometrical parameters but also by the corrosion
381 rate and this explains why this parameter was considered in an iterative measurement
382 procedure that will be presented in detail in part 5.5. The influence of resistivity and the three
383 geometrical parameters is first presented in parts 5.3 and 5.4.

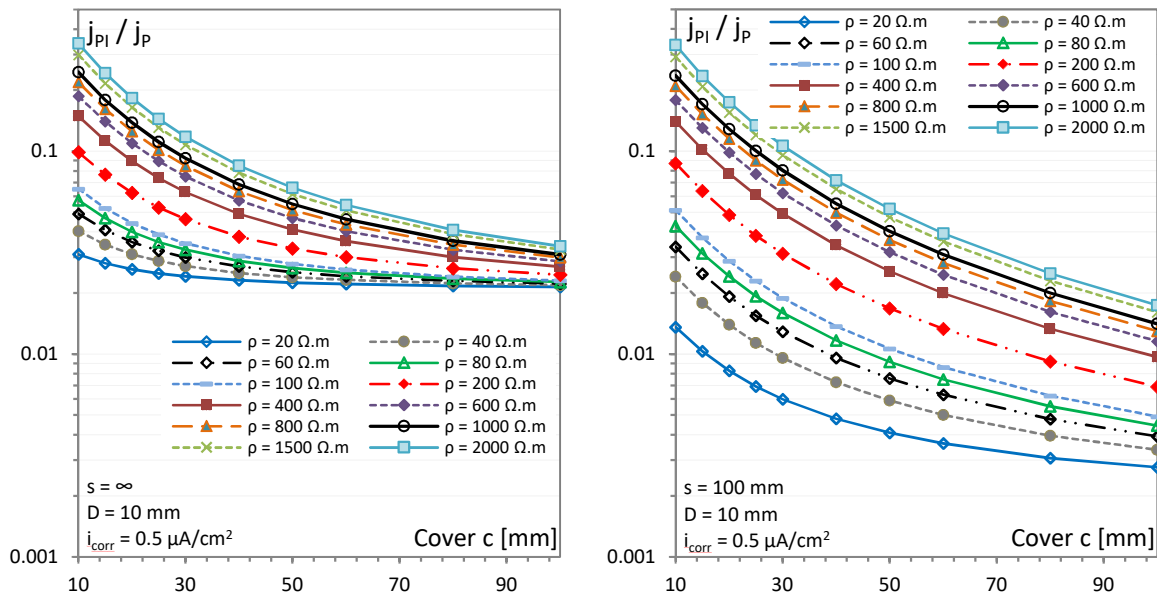
384 **5.3 Current density j_{PI}**

385 To obtain the SLPR $R_{P,s}$ at the PI, both current density j_{PI} and rebar polarization ΔE_P are
386 required. The current density at the PI should be influenced by the concrete resistivity, rebar
387 spacing, cover and rebar diameter as it will modify the current line distribution. All these
388 possible configurations were modelled numerically. This approach aimed first to determine j_{PI}
389 on site, knowing the concrete cover resistivity ρ , rebar spacing s , concrete cover c and rebar
390 diameter D . The ratio between j_{PI} and the current density injected by the CE j_P is shown in
391 Figure 10 for a rebar diameter D of 10 mm. The current density injected by the CE j_P is
392 constant ($j_P \approx 30 \mu A/cm^2$) and is equal to the ratio between the injected current ($J_P = 10 \mu A$)
393 and the CE surface area.

394 A strong influence of the concrete resistivity on the current at the PI is revealed in Figure 10
395 (a) for a single bar. With high resistivity, a large part of the current flows directly from the CE
396 to the PI. Lower resistivity enables wider current distribution over the concrete volume,
397 explaining the lower proportion of current flowing through the PI which was also highlighted
398 in [15,37].

399 Regardless of the concrete resistivity considered, the current density flowing through the PI
400 decreases when the concrete cover is increased. As the concrete cover increases, the current is

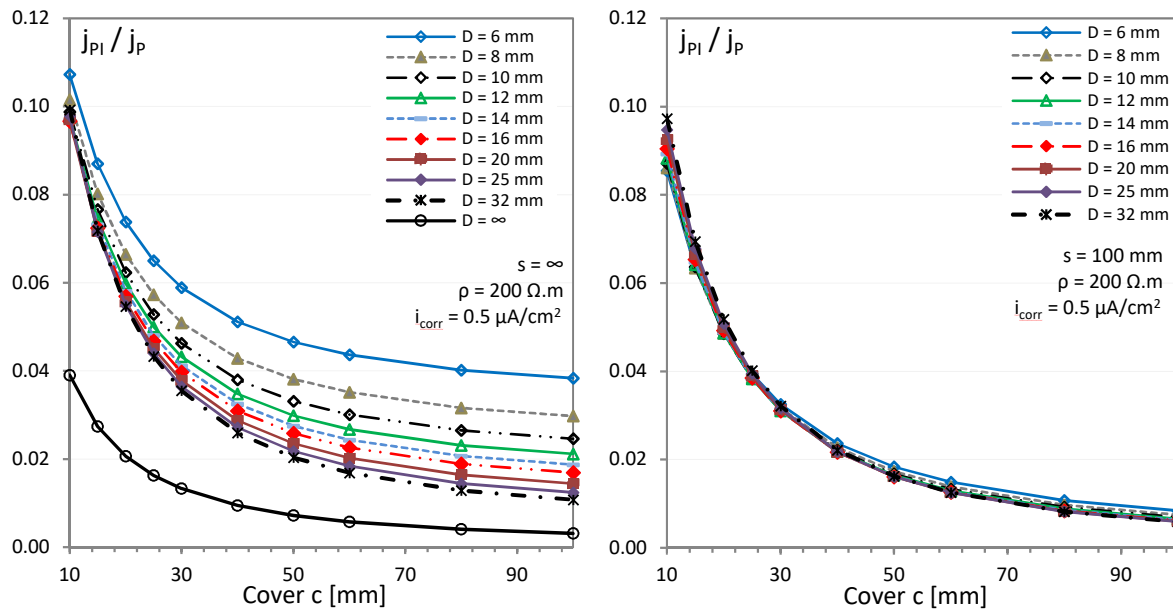
401 spread farther along the rebar, explaining the lower current density right under the RE, at the
 402 PI.



403
 404 **Figure 10. Ratio of the current density at the PI j_{PI} to the current density j_P injected by**
 405 **the CE for a 10 mm rebar diameter, depending on concrete cover for different concrete**
 406 **cover resistivities and for two rebar spacings, $s = \infty$ (a) and $s = 100$ mm (b).**

407 Moreover, the current at the PI j_{PI} is also strongly influenced by the introduction of other
 408 rebars, as demonstrated in Figure 10 (b) for a rebar spacing, s , of 100 mm. For all the concrete
 409 covers and concrete resistivities, the introduction of other rebars is associated with a decrease
 410 of the current at the PI, j_{PI} . This is especially the case for the lower concrete resistivity
 411 because the current has other exit points that it can reach easily because of the low resistivity.
 412 The influence of both rebar diameter and rebar spacing on the ratio between j_{PI} and the current
 413 density injected by the CE, j_P , is quantified in Figure 11. In Figure 11 (a), only one rebar is
 414 considered ($s = \infty$). As previously observed, the current density at the PI decreases with
 415 concrete cover. The rebar diameter also influences the current distribution. With smaller
 416 diameter, the surface available for the current to pass is smaller, which explains why the

417 current density j_{PI} is higher. For a metal plate ($D = \infty$), the ratio j_{PI}/j_P is minimal because the
 418 current can flow out of the concrete through the larger available area.



419
 420 **Figure 11. Ratio of the current density at the PI to injected current density j_P , for $\rho =$**
 421 **$200 \Omega.m$ and for 2 rebar spacings: ∞ (a) and 100 mm (b).**

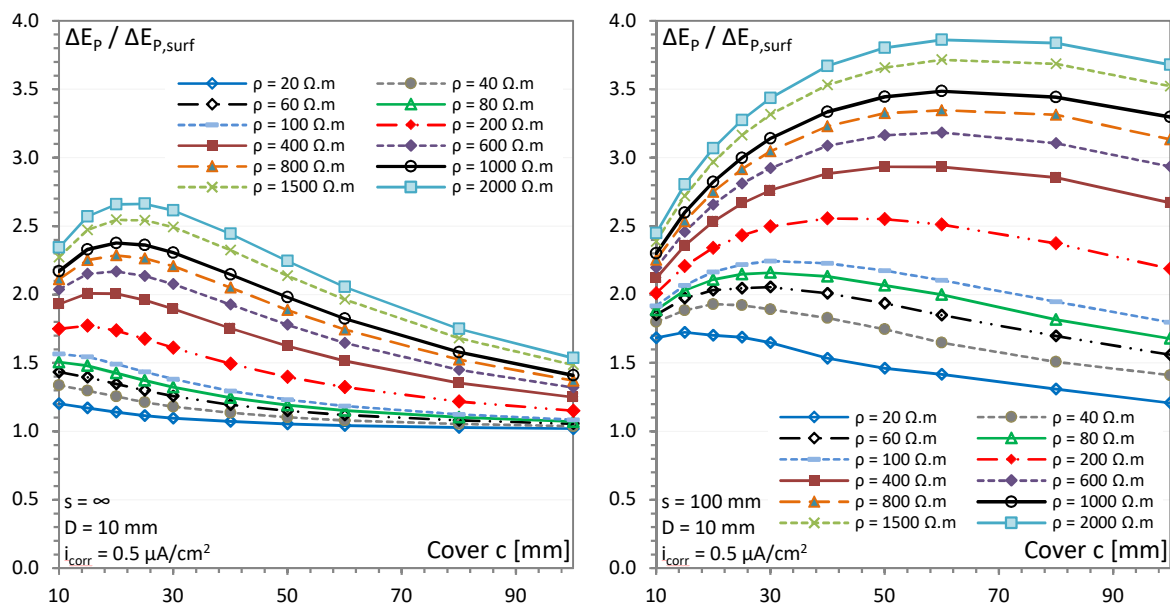
422 Figure 11 (b) represents the same current density ratio when other rebars, spaced 100 mm
 423 apart, are introduced. Regardless of the rebar diameter or concrete cover considered, the
 424 current density at the PI is slightly decreased because of the presence of other rebars. These
 425 new rebars receive part of the injected current, which explains the current density reduction at
 426 the PI. However, because the resistivity is not very low, the introduction of other rebars does
 427 not modify the ratio j_{PI}/j_P very much for this particular example. It has already been
 428 demonstrated in Figure 10 (a) and (b) ($\rho = 200 \Omega.m$ - red dotted curve with diamond shaped
 429 markers) that the transition from a single bar to a 100 mm rebar spacing does not markedly
 430 modify j_{PI}/j_P for $\rho = 200 \Omega.m$. Moreover, the differences observed in the ratio j_{PI}/j_P for the
 431 higher concrete covers (Figure 11 (a)) are now negligible. These two figures give an
 432 understanding of the influence of rebar diameter and rebar spacing on the current density at
 433 the PI j_{PI} . This demonstration concerns a concrete resistivity of $200 \Omega.m$ and a corrosion rate

434 of $0.5 \mu\text{A}/\text{cm}^2$ but similar conclusions can be obtained for other concrete resistivities and
 435 corrosion rates.

436 5.4 Rebar polarization ΔE_P

437 To determine the SLPR, the rebar polarization ΔE_P is also required. The concrete cover and
 438 resistivity, and the rebar diameter and spacing influence the current distribution and, again,
 439 have to be taken into account to determine the rebar polarization.

440 The example in Figure 7 demonstrates that the rebar polarization and the polarization
 441 measured on the surface are not equal (see also schematic layout in Figure 5 (d)). In order to
 442 determine the rebar polarization, ΔE_P , based on the potential measured on the surface $\Delta E_{P,\text{surf}}$,
 443 Figure 12 shows an example of 10 mm rebar(s). For a single bar (Figure 12 (a)) and resistivity
 444 lower than or equal to $100 \Omega\cdot\text{m}$, the ratio $\Delta E_P/\Delta E_{P,\text{surf}}$ decreases when the concrete cover
 445 increases. Different behaviour is observed for resistivity higher than $100 \Omega\cdot\text{m}$: the ratio is
 446 maximal for concrete covers of around 20 mm, which is usually the case on site.

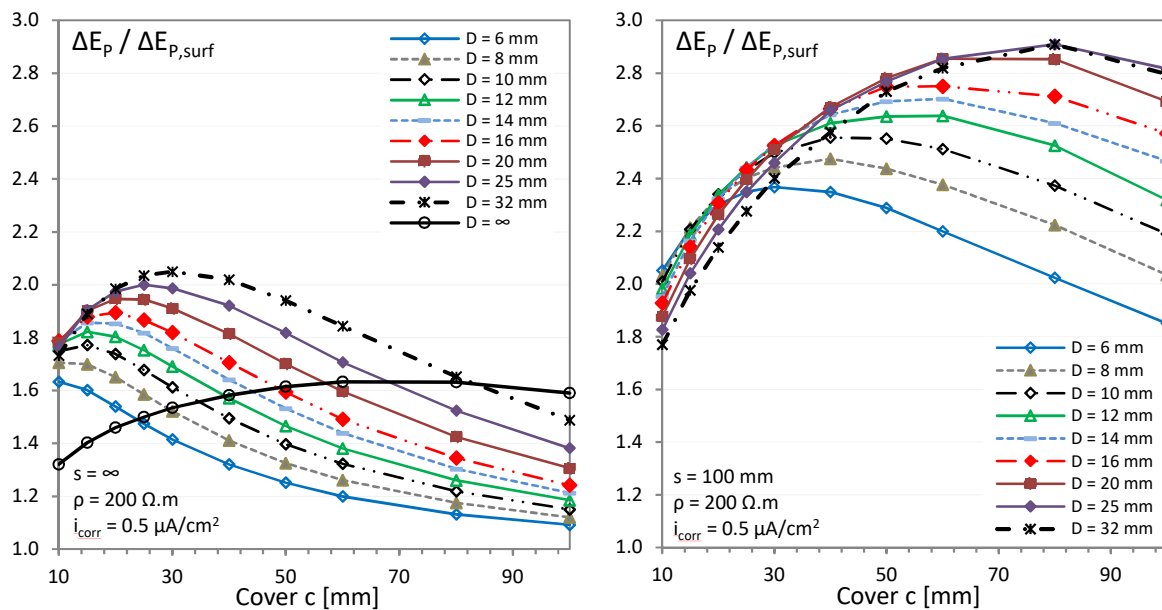


447
 448 **Figure 12. Ratio of the rebar polarization to the polarization measured on the surface**
 449 **for a 10 mm diameter rebar, according to concrete cover depth for different concrete**
 450 **cover resistivities and for two rebar spacings, $s = \infty$ (a) and $s = 100$ mm (b).**

451 It can be observed on Figure 12 that the rebar polarization, ΔE_P , is always higher than the
 452 polarization measured on the surface, $\Delta E_{P,surf}$. Thus, if the rebar polarization is wrongly
 453 determined as the difference between the polarization measured on the surface in the steady
 454 state minus the instantaneous ohmic drop, the rebar polarization and the SLPR are
 455 overestimated. Thus, the corrosion rate can be dangerously underestimated.

456 The fact that the $\Delta E_P/\Delta E_{P,surf}$ ratio increases with resistivity can be explained by the fact that
 457 higher resistivity leads to more concentrated current lines right under the CE. As observed for
 458 the ratio j_P/j_P , the ratio $\Delta E_P/\Delta E_{P,surf}$ is also influenced by the introduction of other rebars as
 459 demonstrated in Figure 12 (b). The ratio $\Delta E_P/\Delta E_{P,surf}$ increases significantly with the
 460 introduction of other rebars because their presence tends to decrease the resistance of the
 461 system, leading to a decrease of the polarization measured at the surface.

462 The influence of rebar diameter is presented in Figure 13 for a $200 \Omega.m$ resistivity and two
 463 rebar spacings ($s = \infty$ (a) and $s = 100 \text{ mm}$ (b)). As demonstrated for the ratio j_P/j_P (Figure 11),
 464 the ratio $\Delta E_P/\Delta E_{P,surf}$ is also influenced by the rebar diameter, whatever the spacing factor
 465 considered.



466

467 **Figure 13. Ratio of the rebar polarization to the polarization measured on the surface**
468 **according to concrete cover for various rebar and for two rebar spacings, $s = \infty$ (a) and**
469 **$s = 100$ mm (b).**

470 For a metal plate ($D = \infty$), the ratio $\Delta E_P/\Delta E_{P,surf}$ exhibits a different evolution according to the
471 concrete cover, which is associated with a different current distribution in the concrete. The
472 previous graphs (Figure 10, Figure 11, Figure 12, Figure 13) were obtained for a numerical
473 corrosion rate of $0.5 \mu A/cm^2$. As significantly different values of these ratios were obtained
474 with the two other corrosion rates modelled (i.e. i_{corr} of 0.1 and $1 \mu A/cm^2$), an iterative
475 approach was developed and is presented in the next part.

476

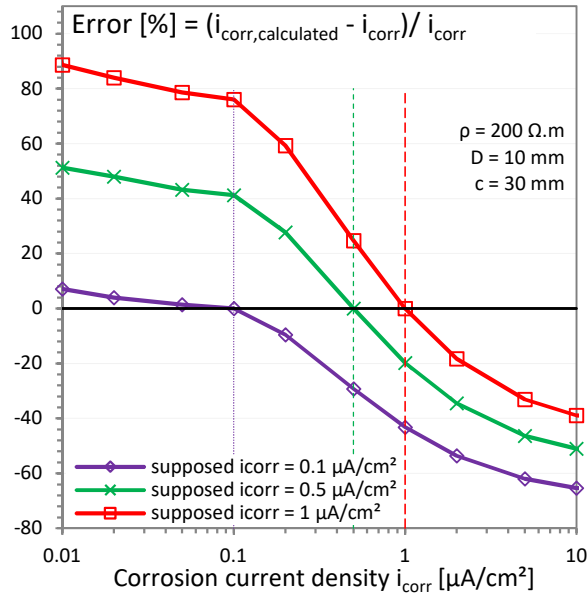
477

478 **5.5 Iterative measurement procedure**

479 In order to visualize the influence of the supposed corrosion rate in the calculation of
480 corrosion rate, Figure 14 is introduced. It presents the error of the calculated corrosion current
481 density $i_{corr,calculated}$ depending on the corrosion current density i_{corr} for an example with a
482 single 10 mm diameter rebar, a concrete cover of 30 mm and a concrete cover resistivity of
483 $200 \Omega.m$. This error was represented for three supposed corrosion current density (i.e. 0.1 , 0.5
484 and $1 \mu A/cm^2$). The calculated corrosion rates $i_{corr,calculated}$ were calculated using the potential
485 measured on the surface, $\Delta E_{P,surf}$ and the ratios j_P/j_P and $\Delta E_P/\Delta E_{P,surf}$ determined for each
486 supposed corrosion rate. It is clear in Figure 14 that the calculated corrosion rate $i_{corr,calculated}$ is
487 equal to the corrosion current density i_{corr} when the supposed corrosion rate is correct (error =
488 0% in Figure 14). Figure 14 also revealed that it is very important to use a supposed
489 corrosion rate close to the real corrosion rate. For instance, if the rebar corrosion rate is 0.1
490 $\mu A/cm^2$ (purple dotted vertical curve) and the supposed corrosion rate is $1 \mu A/cm^2$ (red curve

491 with square markers), the error reach 76 %. The error measured can be important which
 492 explain that an iterative approach must be performed.

493



494

495 **Figure 14. Error in corrosion rate calculation depending on the corrosion rate of the**
 496 **rebar for three supposed corrosion rate (0.1, 0.5 and 1 $\mu\text{A}/\text{cm}^2$). This example is**
 497 **presented for a single bar, $D = 10$ mm, $c = 30$ mm and $\rho = 200$ $\Omega\cdot\text{m}$.**

498 The on-site measurement process and the automatic iterative corrosion rate calculation is
 499 detailed in Figure 15. The different potentials (E_{corr} , ΔE_{tot} and ΔE_{Ω}) useful for SLPR
 500 measurement are recorded by the RE during the transient polarization measurement and are
 501 employed for SLPR measurement here thanks the graphs plotted for j_{PI}/j_P and $\Delta E_P/\Delta E_{P,surf}$.
 502 The left part of Figure 15 deals with the resistivity calculation and is similar to what was
 503 presented in a previous article [8].

504 The right part presents the algorithm used for rebar corrosion rate estimation. The three
 505 supposed values of corrosion rate employed for numerical simulations (0.1, 0.5 and
 506 $1 \mu\text{A}/\text{cm}^2$) are stored in the vector $i_{corr,vec}$. The ratios j_{PI}/j_P and $\Delta E_P/\Delta E_{P,surf}$ are determined

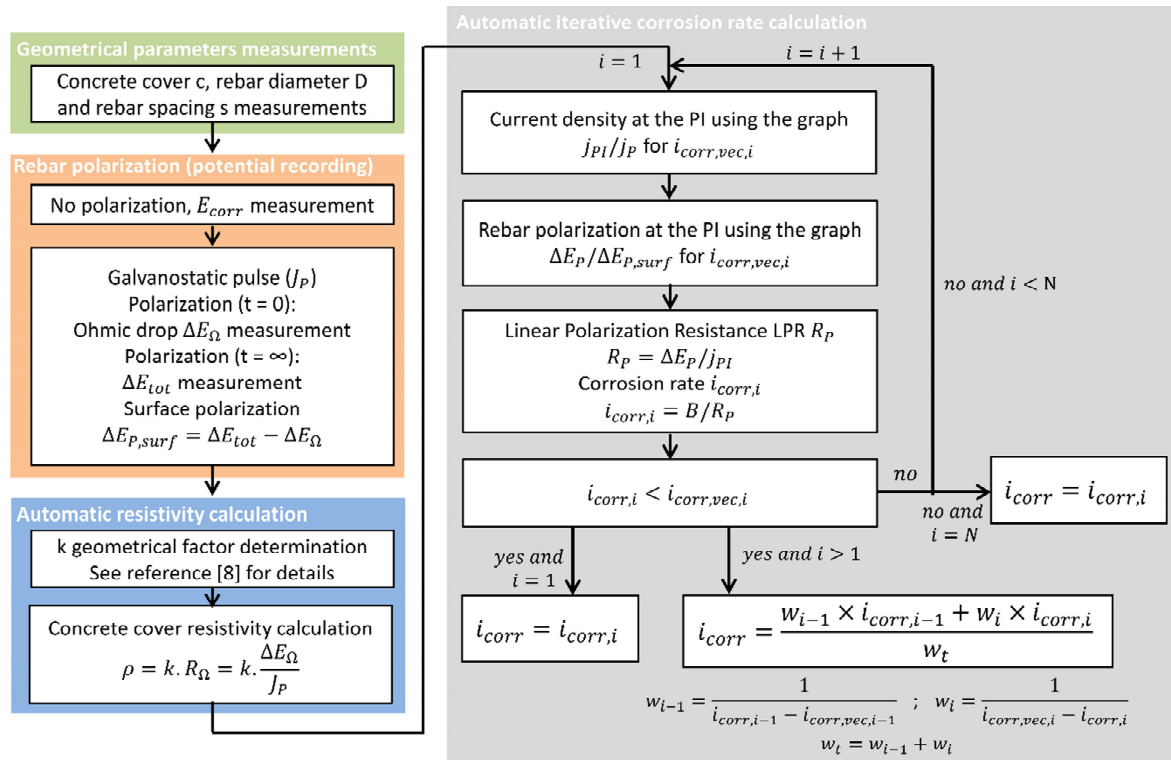
507 using the simulations based on the first value of $i_{\text{corr,vec},1}$ (i.e. $0.1 \mu\text{A}/\text{cm}^2$ here) depending on
508 the resistivity calculated in the left part of Figure 15.

509 The ratios $j_{\text{PI}}/j_{\text{P}}$ and $\Delta E_{\text{P}}/\Delta E_{\text{P,surf}}$ are calculated for a limited number of modelled resistivities
510 (17 different resistivities, see Table 1). The resistivities measured on site are different from
511 the resistivities modelled. Some linear interpolations between the graphs obtained with the
512 adjacent modelled resistivity and the resistivity measured on site are automatically calculated
513 by the software developed by the authors to obtain a more accurate estimation of the $j_{\text{PI}}/j_{\text{P}}$ and
514 $\Delta E_{\text{P}}/\Delta E_{\text{P,surf}}$ ratios.

515 Using these two ratios for the first supposed corrosion rate $i_{\text{corr,vec},1}$ and the measured
516 potential $\Delta E_{\text{P,surf}}$, SLPR and then the first corrosion rate, $i_{\text{corr},1}$, can be calculated and
517 compared to the supposed corrosion rate $i_{\text{corr,vec},1}$. If the calculated value is lower than $i_{\text{corr,vec},1}$,
518 which is the smallest corrosion rate for which the simulations were performed, the calculated
519 value is kept and corresponds to a negligible corrosion rate. If the calculated value is higher, a
520 second corrosion rate is calculated using the second supposed corrosion rate (i.e. $i_{\text{corr,vec},2} = 0.5$
521 $\mu\text{A}/\text{cm}^2$ here). If the second calculated corrosion rate value $i_{\text{corr},2}$ is higher than the second
522 supposed corrosion rate value $i_{\text{corr,vec},2}$, another iterative loop is performed. Otherwise, if
523 $i_{\text{corr},2} < i_{\text{corr,vec},2}$ (i.e. $0.1 < i_{\text{corr},2} < 0.5 \mu\text{A}/\text{cm}^2$ here), the final output corrosion rate value i_{corr} is
524 determined using a weighted average between the first and the second calculated values
525 ($i_{\text{corr},1}$ and $i_{\text{corr},2}$). The highest weight is given to the calculated value that is closest to the
526 supposed value. Finally, after all the possible iterative looping (i.e. a maximum of three loops
527 here), if the last calculated value is higher than the supposed value, the final output corrosion
528 rate value i_{corr} will be the last one calculated.

529 This algorithm may appear unnecessarily complex as the simulations have only been
530 performed for three corrosion rates, i_{corr} , for the moment. However, additional supposed

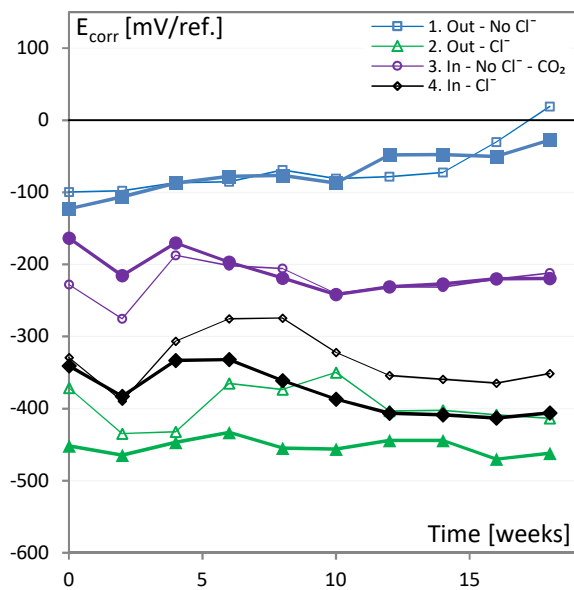
531 corrosion rates will be progressively added in order to increase the precision of the calculation
 532 and this is why the algorithm is presented in its most general form.



533
 534 **Figure 15. Procedure for the SLPR and corrosion rate measurement on site.**

535 **6 Experimental measurements**

536 The probe and associated measurement procedure were used to determine the rebar corrosion
 537 potential, concrete cover resistivity and rebar corrosion rate on the rebars of eight slabs during
 538 18 weeks. In order to limit the number of figures in this article, we chose to calculate the
 539 average value of these parameters for the six concrete covers (Figure 3) at each time point and
 540 to present the results in three figures (Figure 16, Figure 17, Figure 18).



541

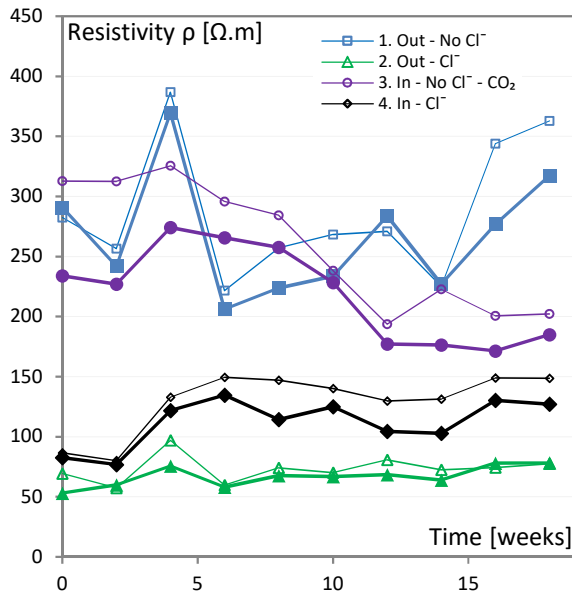
542 **Figure 16. Evolution of the average corrosion potential E_{corr} measured on the eight slabs.**

543 **Thick curves are for 20 mm rebars, thin curves are for 6 mm rebars.**

544 The evolution of the corrosion potentials is presented in Figure 16. The first notable feature is
 545 that, whatever the curing condition considered, the two rebars in the same curing conditions
 546 follow the same general trend. However, for both concrete slabs containing chloride (cures 2
 547 and 4) the corrosion potential is lower (around 50 mV/ref) for 20 mm rebars.

548 The slabs without chloride, placed outdoors (cure 1) present the highest corrosion potential.
 549 During the 18 weeks of measurements, the corrosion potential increased slightly, from around
 550 - 100 mV/ref. to 0 mV/ref., which indicates an extremely low corrosion risk. In contrast, the
 551 slabs containing chlorides and placed outdoors have the lowest corrosion potentials observed.
 552 They are around - 430 mV/ref. after 18 weeks, which indicates high corrosion risk. The slabs
 553 prepared without chloride and placed in an ordinary indoor environment (cure 4) or placed in
 554 the carbonation chamber (cure 3) have intermediate corrosion potentials. The corrosion
 555 potentials of slabs prepared with chlorides and placed indoors are around - 200 mV/ref.,
 556 which indicates that the carbonation front probably reached the rebars. The extremely high
 557 water/cement ratio led to very high porosity and the CO_2 content of the carbonation chamber

558 (50 %) was very high. These two facts explain the fast carbonation and associated
 559 intermediate corrosion potentials observed. Finally, the slabs stored indoors and prepared with
 560 chloride exhibit low corrosion potentials (around - 370 mV/ref.). As observed for the other
 561 slabs prepared with chloride and stored outside (cure 2), the high chloride content introduced
 562 during slab fabrication probably avoided the formation of a passive layer.

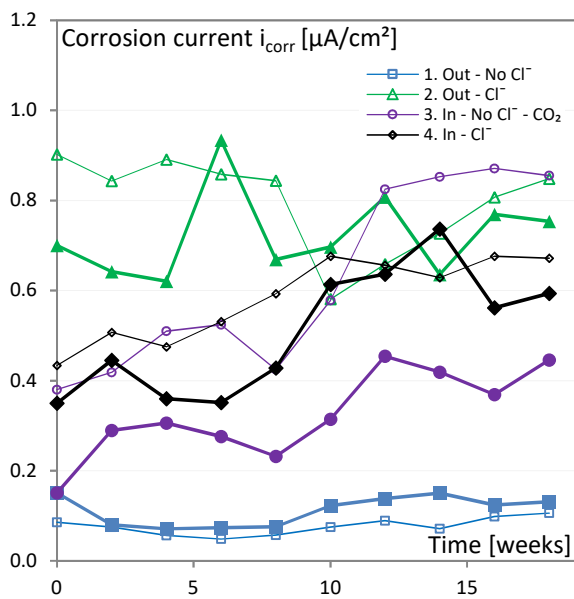


563
 564 **Figure 17. Evolution of the average concrete cover resistivity ρ measured on the eight**
 565 **slabs. Thick curves are for 20 mm rebars, thin curves are for 6 mm rebars.**

566 The concrete cover resistivity evolution is presented in Figure 17. On the one hand, the slabs
 567 prepared without chloride and placed outdoors exhibit the highest concrete cover resistivity
 568 variation, which can be attributed to the hydrothermal variations (rain, temperature, etc.).
 569 Resistivities are between 200 and 400 $\Omega.m$, which is quite small for concrete but can be
 570 explained by the extremely high water/binder ratio. The average coefficient of variation
 571 (standard deviation / average) is 19% for these two slabs (cure 1).

572 On the other hand, the slabs kept in the same conditions but prepared with chloride (cure 2)
 573 have very low resistivity (around 70 $\Omega.m$). The presence of chloride logically decreased the
 574 concrete resistivity of the specimens and the average coefficient of variation is 14%.. Again,

575 the slabs placed indoors, prepared with chloride (cure 4) and placed in the carbonation
 576 chamber (cure 3) present intermediate behaviours. The resistivity of the slabs stored indoors
 577 and prepared with chloride have low values that seem to be nearly stable (average of 120
 578 Ω .m, average coefficient of variation of 19%) at the end of the 18 weeks of experiments. The
 579 slabs placed indoors under carbonation (50% CO₂ and 65% RH - cure 3) show slightly
 580 decreasing resistivity values that seem to have stabilized around 180 Ω .m.
 581 The measured resistivities are in agreement with the two different exposure conditions and the
 582 presence or absence of chloride. Note that the measured values are relatively low compared to
 583 what can be measured on site for ordinary concrete because of the low performance concrete
 584 employed.



585
 586 **Figure 18. Evolution of the average corrosion rate i_{corr} measured on the eight slabs.**
 587 **Thick curves are for 20 mm rebars, thin curves are for 6 mm rebars. Curves numbered**
 588 **2 and 4 are false because they were calculated assuming uniform corrosion.**

589 Finally, corrosion rate evolution is presented in Figure 18. The lowest corrosion rate values
 590 were obtained for the slabs placed outdoors and prepared without chloride. The measured

591 values are not negligible as some of them are higher than $0.1 \mu\text{A}/\text{cm}^2$ (see corrosion levels in
592 [16]).

593 The corrosion rate of the slab placed in the carbonation chamber is already high, which
594 indicates that the rebar passivated layer was destroyed due to the fast ingress of CO_2 . This is
595 in agreement with the measured corrosion potentials (Figure 16).

596 The measurement procedure developed in this paper is based on uniform corrosion. However,
597 different papers [43–45] have proved that the chloride ingress causes macrocell corrosion in
598 which the active anode and the passive cathode are spatially separated. It is currently
599 impossible to determine the active surface area, and thus to calculate the local corrosion rate,
600 without destructive tests. The corrosion values obtained on both slabs containing chloride
601 (cures 2 and 4) are presented but the authors insist on the fact that the corrosion rate values
602 presented are not correct. They are apparent corrosion rates. At the end of the 18 weeks of
603 experiments, based on the method developed, which assumes uniform corrosion, the
604 estimated corrosion rates measured on these two slabs were between 0.6 and $1.2 \mu\text{A}/\text{cm}^2$.
605 These values are certainly underestimated as the local corrosion rate at the anode might be
606 much higher. Thus, this probe and the associated measurement principle cannot be applied to
607 determine the corrosion rate when concrete is in presence of chlorides but an apparent
608 corrosion rate can be calculated. As far as we know, there are no devices that can be
609 employed at present to non-destructively determine the rebar corrosion rate for macrocell
610 corrosion. However, the evolution of the apparent corrosion rate will give precious
611 information concerning the evolution of the corrosion state of the structure under inspection.
612 Moreover, the probe and associated measurement principle can be used to determine both the
613 rebar corrosion potential (no polarization) and the concrete cover resistivity as the rebar is
614 short-circuited in both micro and macrocell corrosion

615 7 Conclusions

616 A new probe with a smaller counter electrode than in previous probes has been developed in
617 order to evaluate the corrosion state of reinforced concrete structures. An electrical
618 connection has to be made to the rebar and then galvanostic polarization is performed. No
619 guard ring is used. Three-dimensional numerical simulations are the only way to reliably
620 understand the distribution of polarizing current. In that way, the measurement was
621 numerically modelled in order to convert the potential evolution measured on the surface to
622 the rebar corrosion rate. The following conclusions can be drawn:

- 623 • It is necessary to take the three geometrical parameters of the problem (rebar spacing,
624 s, concrete cover, c, and rebar diameter, D) and the concrete resistivity into account
625 for SLPR $R_{p,s}$ evaluation as they modify the current and potential distribution through
626 the concrete.
- 627 • The polarization measured on the surface, $\Delta E_{P,surf}$, is smaller than the rebar
628 polarization, ΔE_P . The $\Delta E_P/\Delta E_{P,surf}$ ratio is determined numerically and graphs are also
629 proposed in order to convert the potential surface measurement easily.
- 630 • The current density at the Point of Interest, j_{PI} , decreases when the rebar spacing
631 decreases, when the concrete cover increases, or when the rebar diameter increases.
632 Decreasing the concrete resistivity and the rebar corrosion rate also decreases the
633 current density at the PI. The j_{PI}/j_P ratio is determined numerically in order evaluate
634 the current density at the PI easily.

635 A complete methodology for the exploitation of the measurement is finally proposed based on
636 charts and an iterative procedure.

637 The three corrosion parameters evaluated (corrosion potential, concrete cover and rebar
638 corrosion rate) were in good agreement with the composition of the slabs and their curing
639 conditions. However, to improve the iterative measurement procedure developed in this study,

640 other numerical simulations need to be performed with other assumed corrosion rates. The
641 numerical model is also based on a uniform concrete resistivity. However, on site, a resistivity
642 gradient is usually observed and it will modify the measurement. The resistivity measurement
643 method must be validated using other device such as the Wenner on samples without rebars.
644 Moreover, the validation should be performed on concrete that present higher resistivity
645 which would be more representative to field environment. Finally, in order to evaluate the
646 precision of the methodology developed here for corrosion rate assesement, a comparative
647 study between non-destructive measurements made with the DIAMOND probe and
648 destructive mass loss measurements will be carried out.

649

650 **8 References**

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