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Non-destructive measurements for the evaluation of the air permeability of concrete structures

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Title Page with Author Information

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25 **1 Introduction**

26 The durability of concrete structures can be improved by the use of materials with low
27 transfer properties. Quantifying the permeability and diffusion properties of concrete in the
28 field is thus a major issue for civil engineering research. In addition, the air-tightness of the
29 enclosure vessels of nuclear plants has to be tested regularly during the service life of the
30 structures, approximately every 10 years [1,2]. Measuring permeability in the field is a
31 complex task due to the large size of structures (more than 9000 m² of surface for walls with a
32 thickness of approximately 1 metre) and to the number of zones where leaks can potentially
33 occur. Local measurements of concrete permeability can be of great help in completing global
34 measurements on the entire vessel: they improve our knowledge of the heterogeneity of the
35 leaks in the structures and thus help to predict the zones where impermeability may be poor,
36 and to monitor it regularly with a minimum of disturbance to usual operation.

37 Air permeability can be measured in laboratory [3] on specimens drilled from the structures,
38 but such test leads to partial degradation of the structure and non-destructive techniques are
39 usually preferred. Thus, different techniques were developed to measure the air permeability
40 in situ [4–8]. Torrent proposed a device which can be fixed on the surface of the concrete
41 without any holes by vacuum technique [4,9]. The permeability is measured during the
42 unsteady state of the increase of pressure in a cell [4,9]. This paper proposes the comparison
43 of different techniques of air permeability measurement in laboratory for a use in field.

44 Air permeability is highly dependent on the moisture present in the concrete [10,11] and
45 various non-destructive techniques can be used to determine the saturation degree in porous
46 material, such as resistivity and permittivity [12–18]. The use of such techniques in field is a
47 great challenge. If the dependence of air permeability on saturation degree is known, it is then
48 possible to evaluate the concrete permeability in the field from resistivity or permittivity
49 measurements. It is the second main goal of this paper.

50 Thus, the purpose of this paper is to test the capability of various non-destructive techniques
51 (permeameter devices, capacitive and resistive techniques) to evaluate the leakage flow of
52 concrete structures during their service life or after accidental loading. The methodology used
53 to reach this objective is based on tests at three scales:

- 54 - On usual laboratory samples: preliminary test of the surface permeability technique
55 (samples with diameter 150 mm and thickness 50 mm) and comparison with the
56 reference concrete permeability test (Cembureau permeameter) for different saturation
57 levels; calibration tests of the capacitive and resistive techniques on samples drilled
58 from concrete slabs (samples with diameter 75 mm and thickness 70 mm);
- 59 - On large laboratory slabs: validation of the calibration obtained on samples in
60 laboratory conditions (slabs with dimensions 125 x 250 x 500 mm),
- 61 - In field: comparison of the three techniques on a part of the Vercors mock-up built by
62 EDF to help in the management of the long-term operation of its fleet of Nuclear
63 Power Plants [19,20].

64 The conclusions of this work are not only useful for checking the tightness of structures for
65 nuclear uses. They also confirm the interest of the different techniques used here for following
66 up the durability properties of concrete in the field.

67 **2 Techniques and materials**

68 **2.1 Experimental programme**

69 The objective of the experimental programme was to evaluate the capacity of three non-
70 destructive techniques (based on direct permeability measurement with a surface permeameter
71 and on measurements of the saturation degree by resistivity or permittivity measurements) to
72 quantify the concrete permeability in the field. The programme was divided into three steps.

73 First, usual laboratory samples (diameter 150 mm and thickness 50 mm or diameter 75 mm
74 and thickness 70 mm) were compared and calibrated on laboratory specimens for different
75 saturation degrees: from totally saturated concrete to concrete dried under severe conditions
76 (105°C until the mass of the specimen became constant). Under these conditions, significant
77 cracking could occur and impact the measurements [21,22].

78 Secondly, the techniques were validated on large laboratory slabs (125 x 250 x 500 mm)
79 under different environmental conditions, to represent concrete during the service life of
80 structures (in concrete with high degrees of saturation in stress-free or loaded conditions) or
81 after accidental expositions (damaged by thermo-hydric loading). Four types loading can be
82 distinguished (based on the assumption that the average saturation degree of the concrete of
83 usual enclosure vessels is about 60% [20]):

- 84 - Hydric loading: slabs were subjected to drying at 60 °C to obtain 60 and 30% of
85 saturation,
- 86 - Mechanical loading: slabs at 60% saturation were subjected to uniaxial compressive
87 loading of between 0 and 12 MPa (because enclosure vessels are subjected to about
88 12 MPa of compressive prestressing in the orthoradial direction and to about 7 MPa in
89 the vertical direction),
- 90 - Thermal loading: sealed slabs at 60% of saturation were subjected to 80 °C for 14
91 hours in endogenous conditions (without loss of mass),
- 92 - Thermal-hydric loading: slabs at 60% of saturation were subjected to 150 °C or 200
93 °C for 14 hours.

94 The first two types of loading occur during the service life of the structure, while the last two
95 can occur during accidental situations.

96 In the third step, the three techniques were used on a part of the Vercors mock-up. The
97 saturation degree and the values of concrete permeability evaluated by each technique were
98 compared and discussed.

99 **2.2 Experimental techniques**

100 *2.2.1 Permeability measurements*

101 Three techniques for permeability measurement were used in this work. The evaluation of
102 tightness of the enclosure vessel of a nuclear power plant during usual enclosure tests is based
103 on the measurement of air leakage under 5.2 bars of internal pressure in the whole structure,
104 corresponding to the evaluated pressure reachable in case of accident. In order to complete
105 this global test, local permeability measurement of concrete [4–8] seems to be the most
106 natural option.

107 Usually, concrete permeability is measured in the laboratory by the Cembureau method [3]
108 (Figure 1). The principle is to determine the permeability under pressure during steady flow.
109 The result can be directly used to evaluate the leakage of structures in field. The Cembureau
110 technique is the only method standardized for the measurement of concrete permeability on
111 laboratory specimens but it cannot be used in the field because the tested samples have to be
112 confined to control the air flow. In this work, laboratory specimens were first used to
113 characterize the concrete and compare the different techniques. Cembureau apparent
114 permeability measured for 2 bars of absolute pressure was the first permeability technique
115 used in this work. As this method is standardized, it was chosen to be the reference
116 permeability.

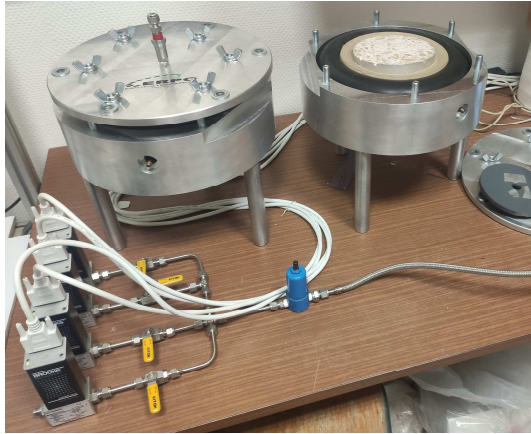


Figure 1: Cembureau apparatus for concrete permeability measurement in laboratory

117 For this study, a second method able to evaluate permeability in the field was necessary. The
118 permeameter proposed by Torrent [4] was used (Figure 2). As this test is based on a vacuum
119 technique and unsteady flow, specific relations [23–26] are necessary so that the permeability
120 deduced from this measurement can be compared to that found with the Cembureau method.
121 The principle of the method to obtain comparable permeability with Torrent and Cembureau
122 permeameters is presented in the following section. As the Torrent permeameter is based on
123 air flow in an unsteady state, the numerical determination of the permeability is not exact,
124 unlike the method using steady flow [23].

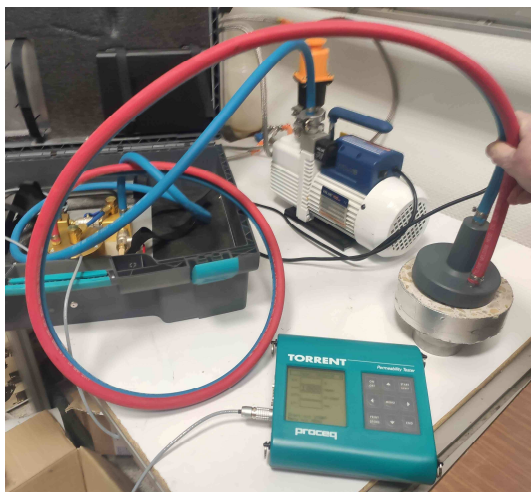


Figure 2: Torrent apparatus for concrete permeability measurement in field

125 Permeability measurement was also performed on the large laboratory slabs under steady
126 flow. The merit of this technique is to evaluate air permeability on volume representative of
127 small structures. Due to potential leakage, measurements of permeability under pressure were
128 difficult to perform on the large slabs used in the second step of the methodology presented.
129 On such large slabs, air-tightness was easier to obtain for measurement in a vacuum.
130 However, it was necessary to use PVC plates stuck and made tight with silicone glue directly
131 on the lateral faces of the slab to obtain a correct sealing. The conditioning was long and
132 needed frequent verification of the sealing. Thus, the air permeability of all the slabs could not
133 be measured in the program. After sealing of the lateral faces of the slabs, a vacuum was
134 applied in a cell glued to one face of the slab (250 x 500 mm). On the opposite face (250 x
135 500 mm), the air flow was measured in the steady state to obtain the air permeability of the
136 whole concrete slab measured in vacuum. The relation necessary to evaluate the permeability
137 under pressure from the measurement in vacuum is presented in [24]. The permeability thus
138 measured was used to validate all the non-destructive methods on the concrete slabs. This
139 third technique is named ‘double-cell’ in the rest of the paper.

140 2.2.2 *Non-destructive techniques for determination of the saturation degree*

141 In this work, resistivity and permittivity techniques were used to determine first the saturation
142 degree of the concrete and then to deduce the air permeability from the measured saturation
143 degree.

144 Resistivity is measured by a Wenner probe (Figure 3) consisting of four electrodes placed a
145 distance ‘a’ apart (a =40 mm). The two outer electrodes inject a direct current, I, while the
146 two inner ones measure the difference of potential, ΔV . The resistivity, ρ , is calculated by the
147 relation [27]:

$$\rho = 2. \pi. a. \frac{\Delta V}{I} \quad \text{Eq. 1}$$

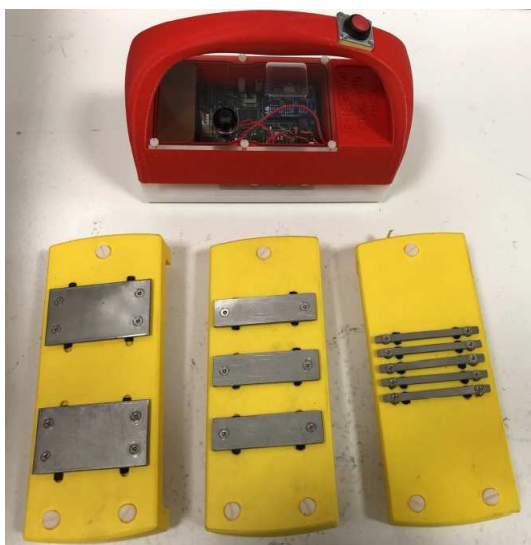
148 The resistivity probe used in this work investigated a depth of concrete of about 15 mm.



Figure 3: Apparatus for concrete resistivity measurement

149 Permittivity measurement uses a device composed of two (or more) electrodes on the outer
150 surface of the concrete (Figure 4). An alternating electric current is applied between the
151 electrodes and so the concrete acts as a capacitor. Any change of concrete capacitance induces
152 a shift in the resonant frequency (around 33 MHz) of the system. This change of capacitance
153 is linked to the change of permittivity of the concrete induced by moisture variation [15]. The
154 apparatus used in this work investigated a depth of concrete of about 15 mm [28].

155



156

Figure 4: Apparatus for concrete permittivity measurement

157 These last two techniques were applied on the surface of the slabs (500x250x120 mm) as well
158 as on the reinforced structure of the Vercors mock-up. Meanwhile, the calibration tests on
159 small samples (75x70 mm) were performed by means of cylindrical cells following the
160 protocol described in [29].

161 **2.3 Concrete and conditioning**

162 Concrete used in this work (Table 1) is representative of a wide range of concrete used in
163 French nuclear plants. The mix-design was similar to the concrete used for the Vercors mock-
164 up built by EDF with usual siliceous limestone aggregates (silica contents of 80% and 5% for
165 the sand and the gravels, respectively). Samples and slabs were cured in lime water at a
166 temperature of 20 ± 2 °C for at least 60 days after casting to obtain a stabilized material
167 regarding cement hydration [30]. The mean compressive strength and instantaneous modulus
168 of the concrete were respectively 49 MPa and 35.3 GPa, with coefficients of variation of
169 about 10%.

170

171 **Table 1.** Concrete mix

Constituents	[kg/m³]
Sand 0/4	830
Gravel 4/11 R	445
Gravel 8/16 R	550
Cement CEM I 52.5 NCE CP2 NF	320
Plasticizer	2.4
Water	167

172

173 Experiments were performed on usual laboratory samples (diameter 150 mm and thickness
 174 50 mm), on large laboratory slabs (125 x 250 x 500 mm) and on cores (diameter 75 mm and
 175 thickness 70 mm) drilled from slabs. Fourteen slabs, made from three concrete batches, were
 176 used. In the following, they are referenced as Bi-j, where ‘i’ is the reference of the batch and
 177 ‘j’, the reference of the slab in the batch.

178 In this study, the saturation degree of all the samples and slabs was controlled. The
 179 conditioning, inspired from [29,31–34], was intended to limit thermo-hydric gradients and
 180 resulting skin cracking. The small samples were first saturated under vacuum. Then, they
 181 were dried with a gradually increasing drying temperature (40 °C to obtain 80% saturation, 50
 182 °C to obtain 60%, 45%, 30% and 10%, and 105 °C to reach the smallest degree of saturation,
 183 taken as 0% in this work). Targeted masses were evaluated from the porosity measured on
 184 other samples cast from the same concrete batch and, once the target mass was reached, the
 185 test samples were placed in sealed conditions (aluminium and sealed bags). They were put
 186 back into the oven (for a period at least equal to the drying time) in order to partially
 187 homogenize the water distribution throughout the sample and thus minimize the impact of
 188 moisture gradient on measurements [34].

189 To evaluate the impact of elevated temperatures on the concrete properties, some samples and
 190 slabs were subjected to thermal loading in an oven preheated to 80, 150 and 200 °C for 14
 191 hours. Before the thermal loading, samples and slabs were wrapped in watertight aluminium.

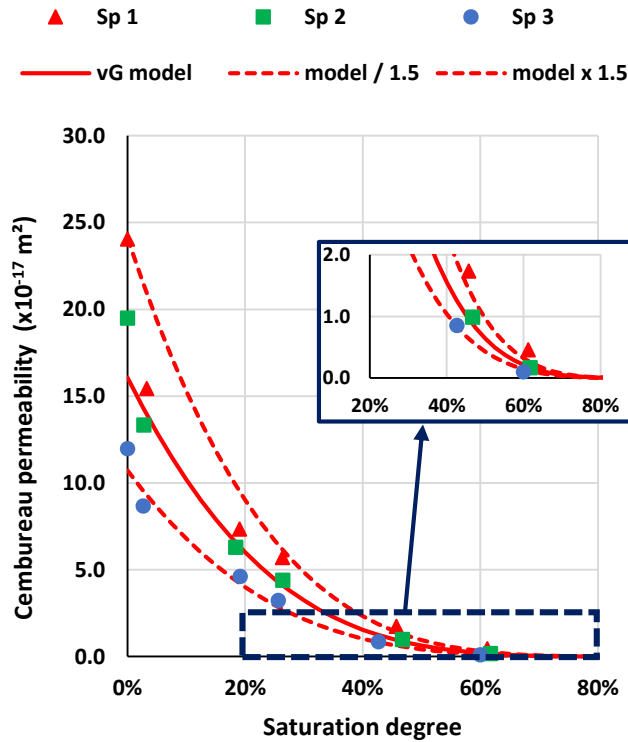
192 Fourteen hours were necessary to reach the target temperature in the slab cores and to
193 maintain this temperature for two hours, as evaluated during the ENDE project [35]. All the
194 properties were measured after the return to ambient temperature. Cylindrical samples
195 (75x70 mm) were cored in the slabs (with or without thermal damage) to evaluate the effect
196 of the thermal loading level on NDT results. Control of the saturation degree was applied to
197 all specimens as previously described (the target was usually obtained with an accuracy of
198 about 2% of saturation degree).

199 **2.4 Air permeability of reference concrete according to saturation degree**

200 The question that arises in this work concerns the capacity of different techniques to allow the
201 air permeability through concrete to be measured in the field. This work can also be used to
202 evaluate the ability of usual laboratory techniques applied to small samples to give an
203 evaluation representative of concrete permeability in real structures.

204 As the Cembureau technique [3] is standardized and commonly used in the laboratory, the
205 apparent permeability of concrete to air, measured by this technique using 2 bars of absolute
206 pressure, is used as a reference for all the work presented here.

207 The evolution of the reference permeability with the saturation degree of concrete is given in
208 Figure 5 for three specimens. The measurements present scatter that is usual for air
209 permeability measurements. The usual variation of air permeability of concrete with the
210 saturation degree [10] can be observed.



211

212 *Figure 5: Concrete permeability measured by Cembureau technique according to the degree of saturation of*
 213 *concrete and van Genuchten's law calibrated on the measurements (red dashed lines represent a variation of*
 214 *50% of the value obtained by the calibrated model)*

215 The dependence of the air permeability of concrete on saturation degree can be evaluated by
 216 van Genuchten's law [36,37], initially defined for soil and later transposed to concrete:

$$k_{S_r} = k_0 \cdot (1 - S_r)^q (1 - S_r^{1/m})^{2m} \quad \text{Eq. 2}$$

217 where k_{S_r} is the apparent permeability for a given saturation degree S_r and k_0 the apparent
 218 permeability for the driest saturation degree (obtained in this programme after drying at 105
 219 °C). q and m are the van Genuchten parameters, which depend on concrete transfer properties.
 220 Van Genuchten parameters, q and m , are determined by calibration of the equation on the
 221 experimental values of permeability obtained for different saturation degrees.

222 The interest of this technique is to measure air permeability in perfect controlled conditions
 223 (unidirectional air flow and steady state). The permeability is thus calculated from the

224 theoretical solution of the transfer problem. However, it can only be performed on specimens
225 in laboratory. For structural concrete, it can only be performed on specimens drilled from the
226 structure leading to partial degradation.

227 Two of the techniques used in this work are able to evaluate the saturation degree of concrete
228 (resistivity and permittivity). Combined with the van Genuchten law evaluated from
229 laboratory measurements, they can be used to evaluate the air permeability of concrete in the
230 field.

231 For usual environmental expositions, the concrete saturation often lies between 30 and 50% at
232 the surface and is often higher in the core of massive structures [20]. Thus, it was chosen to
233 calibrate van Genuchten' law with very low weight (5%) for the two driest saturation degrees
234 (0 and 3%), which are not representative of the humidity state during the service life of usual
235 structures. This gives an evaluation in accordance with measurements of high saturation
236 degrees (see the detail in Figure 5) with correct evaluation of air permeability for the two
237 lowest saturation degrees (Figure 5). The calibration leads to $16.1 \times 10^{-17} \text{ m}^2$, 4.2 and 0.5 for
238 k_0, q and m respectively (the mean deviation between the experimental results and the
239 calibrated equation is about 30% – the correlation coefficient is about 0.94). All the
240 experimental values are located between two lines, which represent the model multiplied or
241 divided by a factor of 1.5. Such discrepancy is usual for concrete air permeability
242 measurements [37].

243 **3 Experimental results**

244 **3.1 Comparison and calibration of NDT for permeability evaluation**

245 The first step of the methodology used here is based on preliminary tests of the three
246 techniques on usual laboratory samples. The aim is to compare or to calibrate the three non-
247 destructive techniques with the reference concrete permeability test presented just above.

248 *3.1.1 Comparison of permeability techniques: laboratory and in the field measurements*

249 The first non-destructive technique used in this work is a technique of measurement of
250 permeability performed at the surface of concrete [4]. For such permeameters, the air flow is
251 obtained with the vacuum technique. First, a vacuum is imposed for 60 seconds in a cell in
252 contact with the concrete surface. Then, the vacuum pump is stopped and the permeability is
253 evaluated during the unsteady state of the increase of pressure in the cell [4]. The merit of this
254 technique lies in its capacity to evaluate concrete permeability in field without any
255 degradation of concrete (the device is attached to the structural concrete thanks to vacuum).
256 However, as the permeability is evaluated during an unsteady state, no exact mathematical
257 solution exists for this physical problem [4]. Simplifying assumptions are thus necessary to
258 assess this transfer property. They lead to numerical approximations for the permeability
259 obtained with such a technique.

260 Yssorches et al. proposed a measurement of permeability based on a vacuum technique in the
261 laboratory [38]. The technique was based on the same principle as the Torrent apparatus
262 (imposing a vacuum on a face of concrete for a certain time, then evaluating the permeability
263 from the pressure increase when the pumping is stopped) but only for fairly thin samples. In
264 such conditions, the permeability evaluated in the first period of pressure increase was not
265 representative of the real permeability. For small samples in the laboratory, the increase
266 became almost linear after a long period of time (at least 15 minutes) and the authors
267 recommend evaluating the permeability from the slope of the increase when the regime is
268 stabilized. For small samples, the stabilization is obtained when the thickness is totally
269 crossed by the air flow. At this time, the profile of pressure is stabilized in the thickness and
270 the regime is pseudo-steady, as indicated in [38]. The regime at the beginning of the pressure
271 increase seems to be disturbed by the modification of the boundary conditions, particularly for
272 a small duration of vacuum [38]. This may be due to the brutal stop of the pumping and

273 strengthened by a moisture gradient in the concrete skin.

274 In the case of laboratory samples, once the air flow is almost constant across the concrete
275 thickness, a pseudo-steady regime is set up and the apparent permeability can be deduced
276 from the Hagen-Poiseuille equation and from the conservation of the air mass between the
277 concrete porosity and the volume of the cell [23,39]:

$$k_{a_psr} = \frac{2 \cdot \mu \cdot L}{A \cdot (P_{atm}^2 - P_c^2)} \cdot V_c \cdot \dot{P}_c \quad Eq. 3$$

278 with k_{a_psr} the apparent permeability (m²) obtained during the pseudo-steady regime (there is
279 no real steady regime in this test as the pressure in the cell increases with time, but the
280 gradient of pressure between the two surfaces of the sample is almost constant as the increase
281 of pressure in the measurement cell is small during the test), μ , the air viscosity (Pa.s), L , the
282 thickness of the samples (m), A , the sample cross-section (m²), P_{atm} , the atmospheric pressure
283 (Pa), V_c , the volume of the cell (m³), P_c , the pressure in the cell (Pa) and \dot{P}_c , the slope of the
284 pressure increase in the cell (Pa.s⁻¹). Following the recommendations of Yssorche et al.[38],
285 the slope \dot{P}_c was evaluated in the present work for the last minutes of the pressure increase
286 (over a duration of 120 seconds).

287 For large concrete thickness, the duration of vacuum time would be too long to expect to
288 perform a permeability measurement in such controlled conditions. The main difficulty is then
289 to evaluate the depth of concrete impacted by the air flow. In his approach, Torrent proposed
290 to evaluate this depth, L_0 , from the mass balance of air moles crossing concrete to reach the
291 central cell during the test [4]:

$$L_0 = \sqrt{\frac{2 \cdot k_{a_t} \cdot P_{atm} \cdot (t_v + t)}{\varphi \cdot \mu}} \quad Eq. 4$$

292 with: k_{a_t} (m²) the unknown permeability of the concrete crossed by the air flow; t_v the

293 vacuum time; t the time after the cessation of pumping; φ the porosity of concrete; and μ
294 (Pa.s) the air viscosity.

295 By combining the two previous equations, it is possible to evaluate the permeability, $k_{a,t}$,
296 from the slope of the pressure increase in the central cell for any time, t , after the pumping
297 stops, by the following equation:

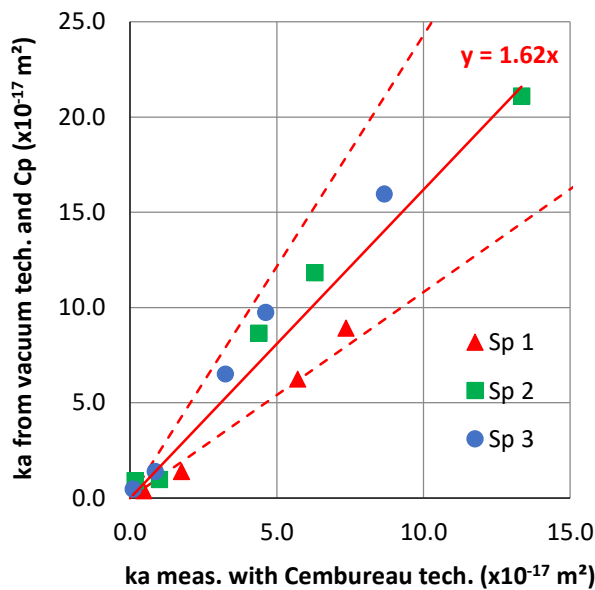
$$k_{a,t} = \frac{8 \cdot \mu}{\varphi} \cdot \left(\frac{V_c}{A}\right)^2 \cdot \frac{P_{atm}}{(P_{atm}^2 - P_c^2)^2} \cdot \dot{P}_c^2 \cdot (t_v + t) \quad Eq. 5$$

298 For specimens with small thickness and large permeability, the air flow rapidly becomes
299 almost constant across the concrete (pseudo-steady state). The permeability can be evaluated
300 from Eq. 3. The previous results obtained in the laboratory have shown that the best
301 evaluation of the permeability will be reached for a long testing time in this case [38]. For
302 specimens with intermediate permeability, the air flow can cross the thickness (so only the
303 external surface is at atmospheric pressure), but the duration of the pressure increase is too
304 short to reach the pseudo-steady state. In this case, evaluating the permeability by Eq. 3 will
305 lead to an overestimation [38]. For specimens with large thickness or small permeability, the
306 air flow does not cross the specimen thickness (a part of the concrete inside the sample is still
307 at atmospheric pressure). The permeability is then evaluated by Eq. 5. If Eq. 5 is used, the
308 evaluation of the permeability is based on the evaluation of the depth of the concrete
309 investigated, L_0 (Eq. 4). The evaluation is based on simplified assumptions and particularly
310 on the linearity of pressure at a certain depth of concrete [4]. The profile is not really linear
311 throughout this depth and this will lead to a misestimation of the permeability.

312 Permeability was measured by the Torrent apparatus for the different degrees of saturation on
313 the sample surface, for the same samples as those used in the Cembureau tests (Figure 5) and
314 the surface permeability was evaluated by the method presented just above. Most of the
315 samples with saturation degrees equal to or lower than 30% were crossed by the air flow

316 during the measurements (permeability evaluated by Eq. 3). None of the samples with higher
 317 saturation degrees were crossed by the air flow (permeability evaluated by Eq. 4 and Eq. 5).

318 Vacuum techniques are commonly used for measuring concrete permeability [4,26,38]. The
 319 mean free path of particles during air flow in a vacuum is different from the mean path under
 320 pressure [40]. The difference has to be considered to evaluate permeability under pressure
 321 from permeability measured in a vacuum, as proposed in [23,24]. For the concrete used in this
 322 work, the apparent permeability for 2 bars of absolute pressure could be deduced from
 323 measurement in vacuum by using a proportionality factor, C_P , of about 0.57 [23]. Figure 6
 324 compares the permeability evaluated by the Cembureau test (under pressure in steady state)
 325 and the permeability evaluated by surface measurement (in vacuum in unsteady state)
 326 corrected for the difference of pressure (coefficient C_P).



327

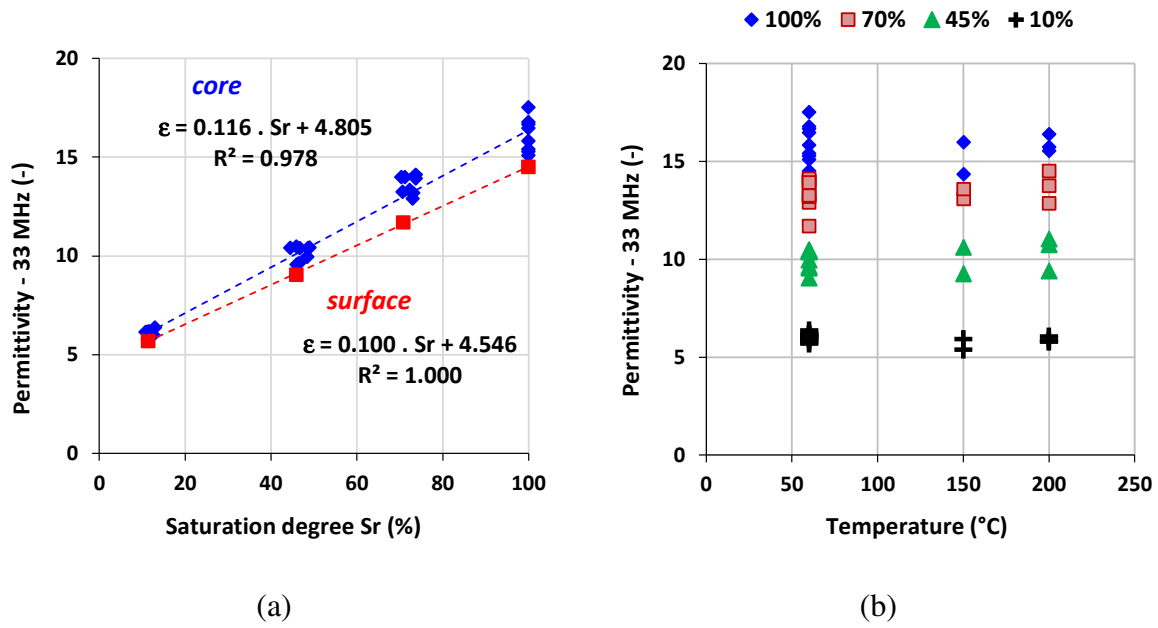
328 *Figure 6: Comparison between the permeability obtained by Cembureau technique for 2 bars of absolute*
 329 *pressure and the surface permeability obtained by Torrent apparatus, evaluated by Eq. 3 and Eq. 5 and*
 330 *corrected with pressure (red dashed lines represent a variation of 50% of the value obtained by the linear*
 331 *equation)*

332 The method leads to an overestimation of the apparent permeability of about 60%. Such a
333 result could be expected due to the short duration of the vacuum (60 seconds) and the short
334 duration of the measurement of the pressure increase (to a maximal increase of 20 mbars) in
335 the central cell of the apparatus (up to 720 seconds of pressure increase). This overestimation
336 is in accordance with the results obtained previously on samples in the literature [38]. The
337 dispersion (ratio of 1.5) is acceptable in comparison with the usual scatter observed for
338 permeability obtained by the Cembureau technique (Figure 5). Works are in progress to
339 validate this approach for other concrete mix-designs.

340 *3.1.2 Calibration of permittivity for permeability evaluation*

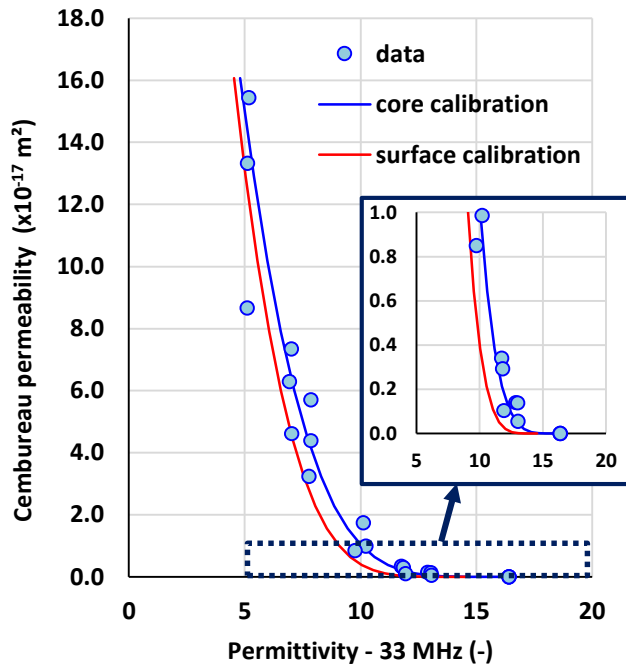
341 Permittivity can be used to evaluate the saturation degree of concrete [15,16]. By combining it
342 with van Genuchten's law evaluated from laboratory measurements (Figure 5), it is then
343 possible to deduce the concrete permeability.

344 The linear dependence of permittivity on saturation degree was evaluated from samples
345 drilled from six slabs before thermo-hydric loading (Figure 7-a). Before loading, slight
346 differences can be observed between the measurements performed on samples taken from the
347 core of the slabs and those taken from the surface (Figure 7-a). They are due to surface effects
348 during casting or ageing, because the surface measurements integrate the properties of the
349 concrete skin, which are different from the properties of the concrete core. The calibration
350 curve obtained on samples representing the surface was preferred for the measurements on
351 slabs and on the Vercors mock-up. Figure 7-b shows the concrete permittivity before (60 °C)
352 and after thermo-hydric loading (150 °C and 200 °C) obtained on cores that were
353 reconditioned after the loading to obtain the measurements on concrete with four different
354 saturation degrees. The damage induced by this loading did not lead to significant differences
355 in concrete permittivity, while the consequences on air permeability were considerable,
356 particularly at high saturation [22].



357 Figure 7: Calibration of permittivity with the saturation degree (a) and impact of thermo-hydric loading on
 358 concrete permittivity (b)

359 From the equations obtained by the calibration of permittivity (Figure 7) and the van
 360 Genuchten law obtained from the Cembureau technique (Eq. 2 - Figure 5), it is possible to
 361 evaluate the concrete permeability and permittivity from the saturation degree (red and blue
 362 lines in Figure 8 for surface and core calibration respectively). Such evaluations can be
 363 compared to permeability measurements obtained by the Cembureau method (data in Figure
 364 8).



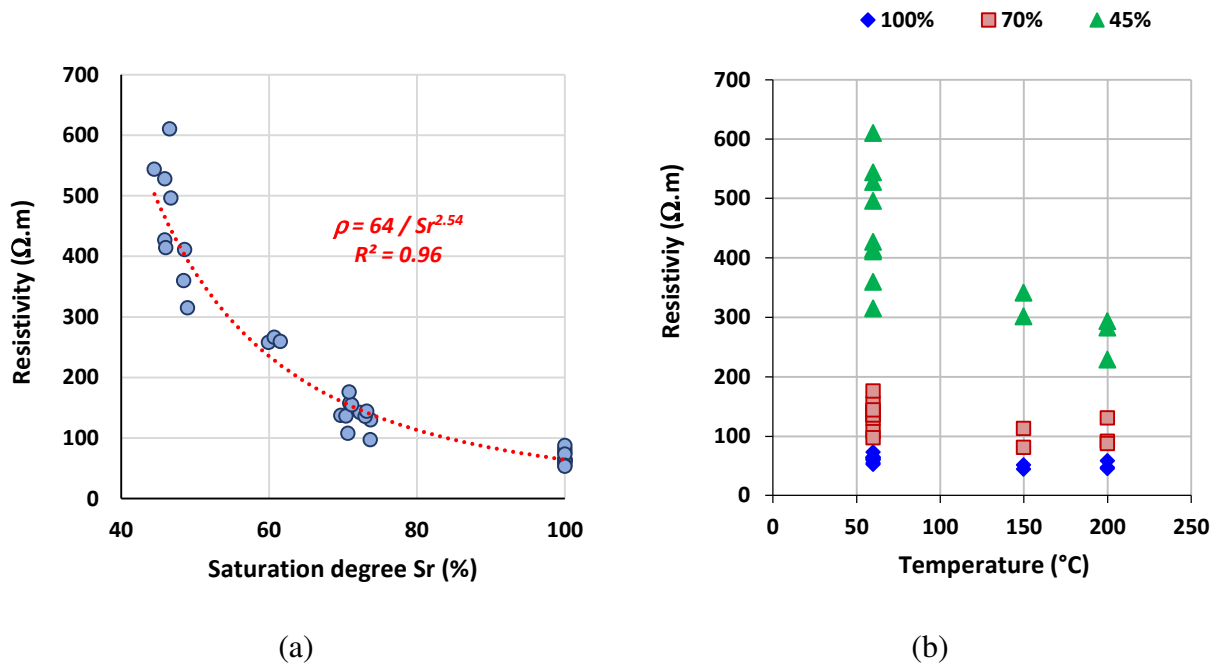
365

366 *Figure 8: Evaluation of permeability from permittivity through van Genuchten's law with the calibrations*
 367 *obtained on samples drilled from the surface and from the core of laboratory slabs*

368 As the calibration was not performed on the same specimens as used for Cembureau tests, this
 369 comparison shows the good reproducibility between the different batches of concrete used for
 370 specimens and for slabs in terms of transfer properties. It also validates the method for the
 371 evaluation of permeability from permittivity on laboratory samples. However, the evaluated
 372 permeability is greatly modified for small variations of permittivity in the range of 5-7 (Figure
 373 8), which corresponds to degrees of saturation lower than 20%. The important interest of this
 374 technique is to be able to evaluate the saturation degree of concrete for a large range of
 375 saturation degree (from 0.2 to 1.0) without any degradation of the structure. However, under
 376 20% of saturation, a small difference of permittivity can lead to a large difference in deduced
 377 permeability. This is not relevant for most of the service life of civil engineering structures
 378 but it can be reached after accidental exposure.

379 3.1.3 Calibration of resistivity for permeability evaluation

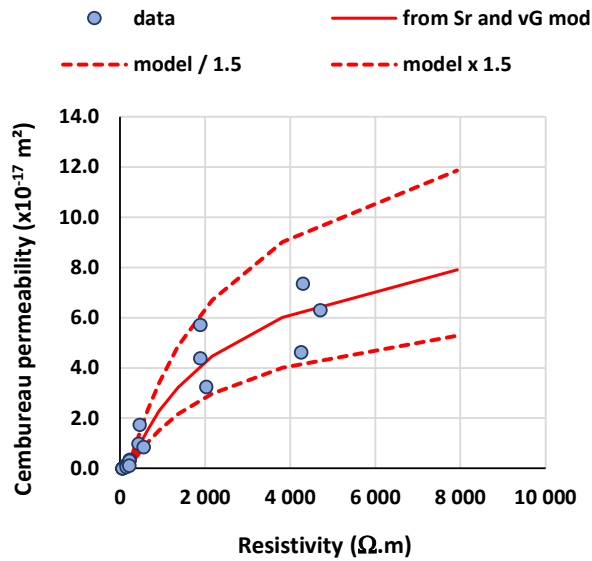
380 The same method was used for resistivity measurement as for permittivity. First, the
381 calibration was performed on laboratory samples so as to be able to evaluate the saturation
382 degree of concrete from resistivity (Figure 9-a). For resistivity, the calibration was performed
383 for high saturation degrees (higher than 45%) as water has to be sufficiently connected in the
384 porosity if concrete resistivity is to be measured. Measurements were performed on samples
385 taken from the core of the slabs and on samples taken from the surface. Few differences were
386 noted between the samples and it was decided to calibrate only one equation for all the
387 measurements (Figure 9-a). As for permittivity, small differences were also observed for the
388 concrete resistivity before and after the thermal loading (Figure 9-b). For high saturation
389 degrees (100%), resistivity was similar for all the samples. For 70% and 45% of saturation,
390 noteworthy scatter was observed for the samples before temperature exposure. The samples
391 came from two different batches, which can partly explain the scatter. Moreover, for 45% of
392 saturation, small differences of the saturation degrees (which were between 44.5 and 49%
393 according to the samples) have a large impact on the resistivity value. The resistivity
394 technique presents the same limit as permittivity but for higher saturation degrees (from about
395 0.5 to 1.0). Moreover, as the conversion model from resistivity to saturation degree is a power
396 function, small variation of low values of resistivity can lead to higher uncertainties for high
397 degrees of saturation ($0.9 < S_r < 1$) than for low degrees of saturation ($0.5 < S_r < 0.6$). This is
398 not the case for permittivity measurements because the conversion model is linear. However,
399 a slight decrease in concrete resistivity can be noted with the temperature of thermo-hydric
400 loading. The decrease in resistivity can be explained by the effect of the cracking induced by
401 the loading. Cracks can lead to new paths of transfer in the concrete and thus to a resistivity
402 decrease. In this experimentation, it is mainly significant for the saturation degree of 45%.



403 *Figure 9: Calibration of resistivity with the saturation degree (a), and impact of thermo-hydric loading on*
 404 *concrete resistivity (b)*

405 From the calibration of resistivity (Figure 9) and the van Genuchten law obtained from the
 406 Cembureau technique, it is possible to extrapolate the evolution of concrete permeability with
 407 resistivity for a higher domain of saturation degrees (Figure 10), in accordance with
 408 measurements performed in the field in the last part of this paper.

409



410

411 *Figure 10: Evaluation of permeability from resistivity through van Genuchten's equation and linear empirical*
 412 *model (red dashed lines represent a variation of 50% of the value obtained by the calibrated equation)*

413 **3.2 Validation on large laboratory slabs**

414 The second intermediate step of the methodology was to use the three previous techniques on
 415 large laboratory slabs (125 x 250 x 500 mm) with different loadings: hydric, mechanical,
 416 thermal and thermal-hydric. The aim was to compare the responses of the three techniques for
 417 these different types of loading and, in some cases, to compare them with a direct global
 418 measurement of permeability performed in vacuum and steady state on the whole slab across
 419 the thickness (flow surface: 250 x 500 mm). The permeability measured on small laboratory
 420 samples with the Cembureau permeameter is also represented on all the figures of Section 4 to
 421 enable a direct comparison of permeability determined on slabs and permeability obtained
 422 during the first characterization on samples. Thus, it is possible to draw conclusions on how
 423 representative permeability measurements performed on samples in the laboratory can be in
 424 evaluations of the permeability of larger elements.

425 *3.2.1 Impact of hydric loading*

426 The saturation degree of concrete in the field can be high in the cores of massive structures
 427 and in locations exposed to rainfall. Usually, a large proportion of the concrete of enclosure

428 vessels has a saturation degree lying between 50 and 60%, but parts of the vessels can be
 429 subject to local drying due to external environmental conditions. In this section, concrete slabs
 430 first soaked in lime water for at least 60 days were exposed to 50 °C to reach 60% and 30% of
 431 saturation. Once the desired saturation was reached, the slabs were wrapped in watertight
 432 aluminium. Mass measurements were performed to verify the efficiency of the packing.

433 Eight slabs were used for this part. The results of measurement for the three non-destructive
 434 techniques and for the double-cell technique are given in Table 2. The lowest saturation
 435 degree was about 30% and no resistivity was measured on any of the three slabs.

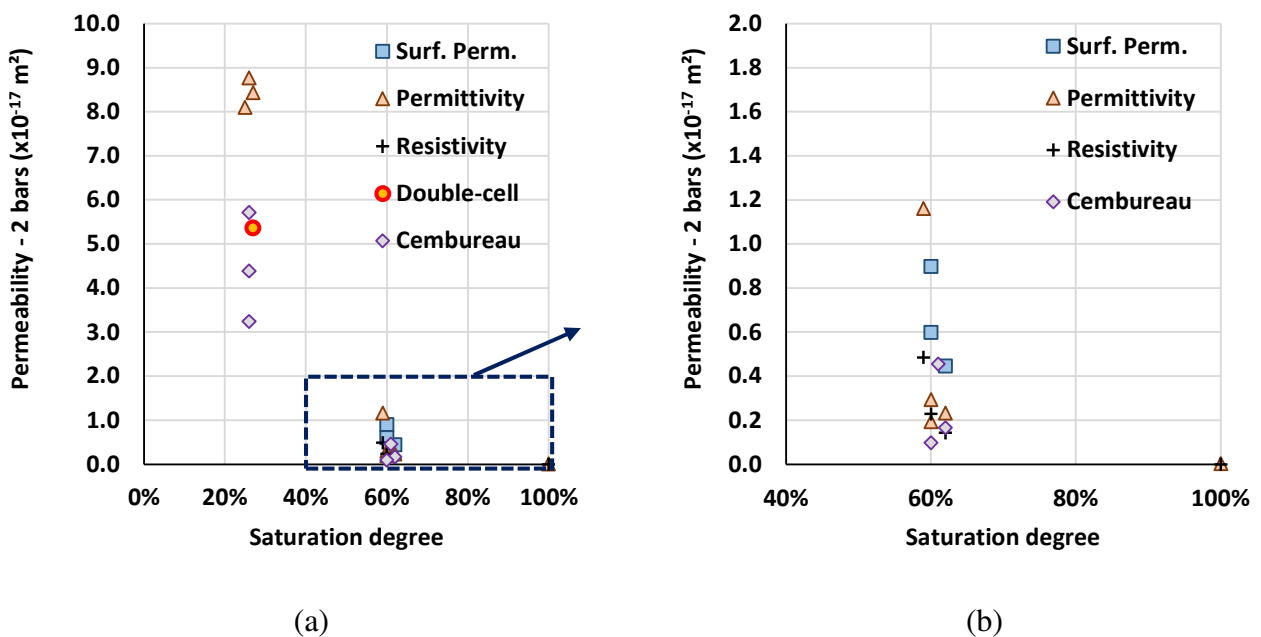
436 *Table 2: Measurements from the different techniques on slabs after hydric loading, and saturation degree (Sr)*
 437 *deduced from permittivity and resistivity*

	Slab	B1-2	B3-10	B2-9	B2-7	B1-3	B1-4	B1-5	B1-6
Sr	%	100	60	62	60	59	27	26	25
Surf. Perm.	$\times 10^{-17} m^2$	-	2.55	1.27	4.70	1.9	-	-	-
Permittivity		12.8	10.3	10.5	10.6	8.3	5.9	5.8	6.0
Deduc. Sr	%	82.7	57.3	59.3	60.8	43.5	13.8	13.0	14.5
Resistivity	$\Omega.m$	64.6	236.2	201	-	305.3	-	-	-
Deduc. Sr	%	99.6	59.8	63.7	-	54.1	-	-	-
Double-cell	$\times 10^{-17} m^2$	-	-	-	-	-	10.0	-	-

438

439 From the measurements given in Table 2, it is possible to evaluate the apparent permeability
 440 at 2 bars as proposed in Section 3. The surface permeability and the double-cell are vacuum
 441 techniques. The apparent permeability for 2 bars of absolute pressure can be deduced from the
 442 measurements in vacuum by applying a proportionality factor, C_P , of about 0.57 [23]. For the
 443 surface permeability, an overestimation of 60% was observed (Figure 6). This overestimation

444 was considered in the evaluation of apparent permeability for 2 bars of absolute pressure by
 445 dividing the results by 1.62. For the permittivity and the resistivity, the saturation degree was
 446 first evaluated from calibrations performed on laboratory samples (Table 2) and the apparent
 447 permeability was then evaluated from van Genuchten's law calibrated on the Cembureau test.
 448 The apparent permeabilities for an absolute pressure of 2 bars evaluated by all the techniques
 449 are shown in Figure 11-a. Figure 11-b presents the details of the results for the highest
 450 saturation degrees.



451 *Figure 11: Evaluation of apparent permeability for an absolute pressure of 2 bars by the different techniques on*
 452 *slabs under hydric loading*

453 For 60% of saturation, no direct double-cell measurement was performed, but the evaluation
 454 by the different techniques can be compared and confronted to the permeability measured on
 455 samples by Cembureau tests (Figure 11-b):

- 456 - Resistivity and 3 measurements on 4 slabs by permittivity gives an evaluation of the
 457 apparent permeability that is of the same order as the permeability measured on
 458 samples with the Cembureau technique;

- 459 - Surface permeability gives a slight overestimation of the apparent permeability. At
460 60% of saturation, the aspiration necessary to obtain the vacuum leads to water
461 movements, evaporation and an overestimation of the permeability due to the long
462 time necessary to reach a pseudo steady state. In addition, homogenization of the
463 water distribution in the slab may not be totally completed at the time of measurement
464 [41]. In presence of a moisture gradient, surface permeability can lead to the
465 permeability being overestimated with respect to the Cembureau measurement;
- 466 - 3 permittivity measurements on 4 slabs gave a correct estimation of air permeability.
467 Only 1 measurement overestimated the permeability. For this slab, the saturation
468 degree was evaluated at 43.5% by the technique, whereas it was checked at 59%. This
469 shows the sensitivity of this measurement to the test conditions, as is also observed in
470 the following section. This sensitivity seems higher than for the other techniques.

471 For one slab compared to the other ones, resistivity jumps from about 200 Ω .m to 305
472 Ω .m for a similar saturation degree (about 60%). This technique is based on the injection of
473 an electrical current in concrete. The electric current is carried by the ions present in the
474 concrete pore solution. It gives reliable results for concrete with high saturation degree (what
475 is usual for massive concrete structures submitted to external environmental conditions) [42].
476 However, for this concrete, it becomes highly nonlinear under 60%, because the solution is no
477 longer continuous in the concrete porosity. Then the results become highly scattered. This
478 effect should be considered when resistivity measurement is used on structures exposed to dry
479 conditions.

480 For 30% of saturation, the air permeabilities measured by the double-cell and by the
481 Cembureau technique on samples were consistent. Permittivity measurements showed small
482 dispersion, but the evaluation overestimated the apparent permeability by almost 60% (Figure
483 11-a). This was due to an underestimation of the saturation degree. Permittivity calibration led

484 to a saturation degree lying between 13 and 14.5 for the three slabs, while it was actually
485 about 25-27% (Table 2). Several difficulties can explain this result:

486 - Permittivity is less sensitive to the saturation degree under 20% because the
487 quantity of water inside the porosity is not great enough [43]. Such conditions of
488 moisture are rare for structures exposed to external conditions, but it is important to
489 highlight the risk of using permittivity in structures exposed to dry conditions without
490 specific consideration [43].

491 - Secondly, to obtain controlled saturation degrees, the slabs were first exposed
492 to drying which leads to moisture gradient. Slabs were then placed in sealed
493 conditions and put back in temperature (for a period of time at least equal to the drying
494 time) in order to homogenize the water distribution throughout the sample. However,
495 movements of water are slower during homogenization than in drying [44]. Thus, the
496 gradient was not totally removed at the end of the period. This effect was greater for
497 the slabs than for small samples. The calibration of the conversion model was
498 performed on small cores with homogenous conditions while measurements on slabs
499 were realized on shuttered surface. It was more difficult to obtain homogenous
500 conditions in reasonable time for the slabs.

501 As the techniques did not investigate the same depth, this conditioning can lead to different
502 scattering between techniques but also, with the global saturation degree obtained by mass
503 measurement.

504 *3.2.2 Impact of mechanical loading*

505 During their service lives, enclosure vessels are subjected to constant compressive stress due
506 to prestressing – usually between 7 and 12 MPa (axial and radial prestressing respectively).
507 For increasing compressive stress lower than 50% of the compressive strength, air
508 permeability of concrete usually shows a slight decrease due to consolidation and pore closing

509 [45,46]. In this work, concrete slabs with 60% of saturation were subjected to compressive
 510 stress of between 0.5 and 12 MPa. Due to the small thickness (125 mm) of the slabs compared
 511 to their height (500 mm), it was difficult to obtain homogeneous compressive stress in the
 512 slabs and some bending was detected during the tests. In the configuration used for this study,
 513 it was not possible to perform the direct measurement with the double-cell, but the results for
 514 each technique can be compared and analysed in regard to the literature.

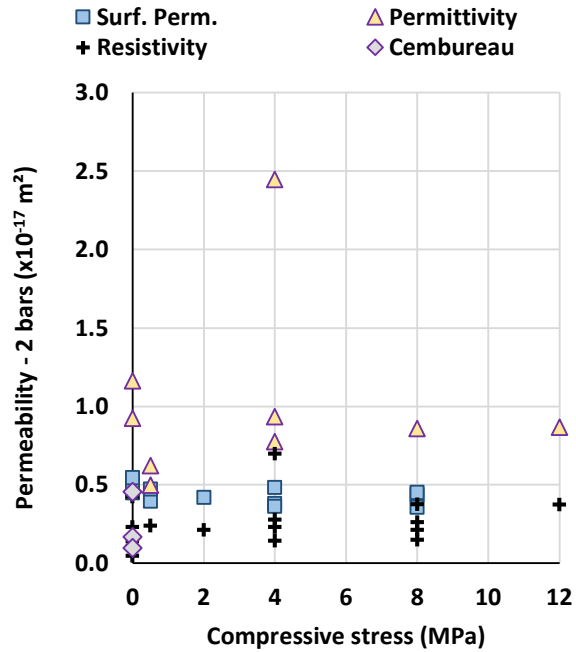
515 Table 3 gives mean values obtained with the three non-destructive techniques for all the
 516 compressive stresses performed in the study. Not all the slabs were investigated at all the
 517 stresses. Most of the mean values were evaluated on 2 or 4 slabs. The measurements were
 518 performed for only one slab for columns marked with an asterisk in Table 3.

519 *Table 3: Mean value from the different techniques on slabs under compressive stress (measurements performed*
 520 *on 5 slabs – B1-1, B1-2, B1-3, B2-6 and B3-8, not all the 6 stresses were performed for all the slabs; columns*
 521 *marked with asterisks indicate that only one slab was measured for this stress state)*

Stress	(MPa)	0	0.5	2*	4	8	12*
Surf. Perm.	$\times 10^{-17} m^2$	1.4	1.2	1.2	2.2	1.2	-
Permittivity	-	9.0	9.5	-	8.8	9.3	9.2
Deduc. Sr	%	44.8	51.4	-	42.7	46.9	46.8
Resistivity	Ωm	219.6	227.0	234.0	273.1	246.3	289.3
Deduc. Sr	%	62.4	60.8	60.0	57.3	59.1	59.8

522

523 The value obtained by the three techniques for each slab was used to evaluate the apparent
 524 permeability based on the calibration performed in Section 3 (Figure 12).



525

526 *Figure 12: Evaluation of apparent permeability at 2 bars given by the different techniques on slabs under*
 527 *mechanical loading*

528 Surface permeability gave a correct evaluation of the apparent permeability compared to
 529 reference measurements.

530 Permittivity measurements evaluated the saturation degree of the slabs at between 33.5% and
 531 52.5% for specific values (the mean values were between 42.7% and 51.4% – Table 3) while
 532 it was controlled at close to 60% by the pre-conditioning. The difference may have been due
 533 to imperfect homogenization of the saturation in the slabs in spite of the specific conditioning.
 534 Due to the difference of the speed of water movement in concrete between sorption and
 535 desorption, homogenization is slower than drying [41]. If the same duration is used for drying
 536 and homogenization, as is usually recommended for such measurements, the saturation
 537 gradient is not totally removed at the end of the conditioning and the surface saturation is
 538 lower than the core saturation. As permittivity apparatus investigated to about 15 mm in
 539 depth, the underestimation could be partially explained by the remaining internal water

540 gradient. This underestimate led to an overestimate of the apparent permeability, particularly
 541 for one slab at 4 MPa.

542 Resistivity led to specific saturation degrees lying between 48.5 and 73% (between 57.3 and
 543 60.8% for mean value) and, thus, the evaluation of apparent permeability through van
 544 Genuchten's law was in accordance with Cembureau measurements.

545 None of the three techniques was sufficiently precise to reliably demonstrate the decrease of
 546 air permeability with the increase of the compressive stress.

547 3.2.3 Impact of thermal loading

548 In this part, slabs at an initial saturation of 60% (and thus preconditioned at 50 °C) were
 549 subjected to 80 °C for 14 hours. At the end of the heating, the global saturation remained
 550 unchanged (verification by weighing of the slabs). The loading can thus be considered as a
 551 thermal load of 30 °C. However, internal water movements could have occurred during the
 552 heating.

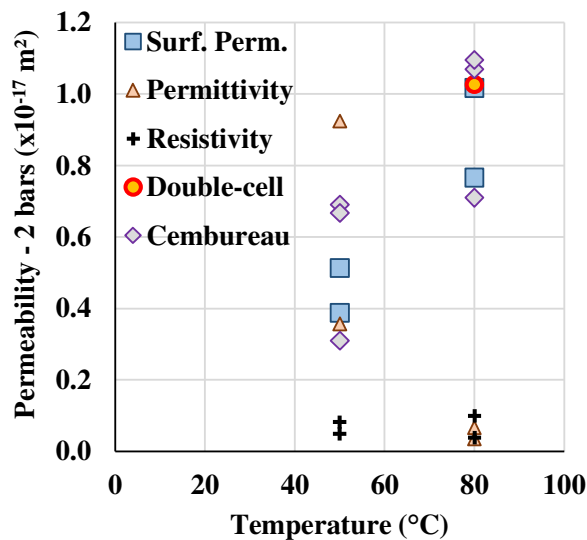
553 Two slabs were used for this part. Results obtained for the three non-destructive techniques
 554 and for the direct measurement with the double-cell technique for one slab are given in Table
 555 4.

556 *Table 4: Measurements from the different techniques on slabs after thermal loading of 30 °C*

	Slab	B2-8		B3-8	
Temperature	°C	50	80	50	80
Surf. Perm.	$\times 10^{-17} m^2$	1.10	2.18	1.46	2.89
Permittivity	-	10.1	11.4	9.2	11.7
Deduc. Sr	%	55.6	68.3	46.1	72.0
Resistivity	$\Omega.m$	177.0	186.2	157.0	149.5
Deduc. Sr	%	67.0	65.7	70.2	71.6
Double-cell	$\times 10^{-17} m^2$		1.8		

557

558 The results were then used to evaluate the apparent permeability (Figure 13) just after the
 559 preconditioning at 50 °C and after the thermal heating at 80 °C. Permeability was also
 560 measured with the Cembureau technique on usual laboratory samples for the same thermal
 561 loading with the same conditioning used for the slabs. Complementary saturation degrees
 562 were also investigated to understand the underlying mechanisms better. The results were
 563 presented and analysed in [22]. Permeability of concrete exposed to 80 °C for 14 hours was
 564 almost twice that of concrete dried at 50 °C for an initial saturation degree of 60%. This can
 565 be explained by physicochemical reactions (decomposition of hydrates) or by the cracking
 566 induced by the differential dilation of aggregate and cement paste [47–50]. The results
 567 obtained on samples with the Cembureau technique have been added to Figure 13 for
 568 comparison with measurements performed on slabs.



569
 570 *Figure 13: Evaluation of apparent permeability at 2 bars with the different techniques on slabs after a thermal*
 571 *loading of 30 °C*

572 The three techniques of permeability measurements (surface permeability, Cembureau and
 573 double-cell) were consistent with the usual scatter found with such techniques.

574 Permittivity gave an evaluation consistent with the permeability technique at 50 °C but the
575 evaluation after the thermal loading at 80 °C was very low. For this case, the technique
576 evaluated the saturation degree as lying between 68% and 72% while it was between 46% and
577 55% at 50 °C (Table 4). In this domain, van Genuchten's law is very non-linear and a small
578 difference in permittivity measurement leads to a great difference in permeability evaluation.
579 As the water content was not modified during the heating, a similar permittivity was expected.

580 The same conclusion can be drawn for resistivity measurement. Resistivity led to saturation
581 degrees lying between 65% and 72% for the two slabs in the two states, which resulted in
582 very low apparent permeability. It was not consistent with permeability measurements
583 performed on the slab but, with apparent permeability of about $0.1 \times 10^{-17} \text{ m}^2$, it remains
584 consistent with the apparent permeability measured on specimens with high saturation degree
585 (Figure 5).

586 In this part, the two electrical techniques seem to lead to an overestimation of the saturation
587 degree. The difference between the saturation degree obtained by these techniques and the
588 global saturation degree obtained by mass measurement can be explained by imperfect
589 homogenization of the saturation in the slabs in spite of the specific conditioning as explained
590 in the previous part. These slight overestimations of the saturation degree had an important
591 impact (one order of magnitude) on the predicted permeability obtained here due to the
592 accumulation of uncertainties. There was not a decimal order on the saturation. But as the
593 evolution of the permeability was quite scattered (factor 2 around 60% of saturation) and very
594 nonlinear in this domain, the prediction of the permeability led to this order of magnitude.
595 Therefore, direct permeability measurements are the most reliable techniques to obtain the
596 most accurate evaluation of the permeability.

597 Permittivity and resistivity were not sensitive to the damage induced by the thermal loading
 598 for the high saturation degree of 60%. This confirms the observations made on cores (Figure
 599 7-b and Figure 9-b).

600 *3.2.4 Impact of thermo-hydric loading*

601 Slabs at 60% of initial saturation were subjected to 150 °C and 200 °C for 14 hours. At the
 602 end of the heating, the slabs were almost dry (in spite of the aluminium wrapping). The slabs
 603 exposed to 150 °C lost slightly less water mass than the slabs exposed to 200 °C. The loading
 604 can thus be considered as thermo-hydric, due to variations of temperature of 100 °C and 150
 605 °C. Such temperatures are usually used to represent accidental conditions in enclosure vessels
 606 [51].

607 Resistivity cannot be measured for dry concrete and thus Table 5 presents the experimental
 608 results for the two other local non-destructive techniques and for the direct measurement by
 609 double-cell in a vacuum.

610 *Table 5: Measurements from the different techniques on slabs after thermo-hydric loading*

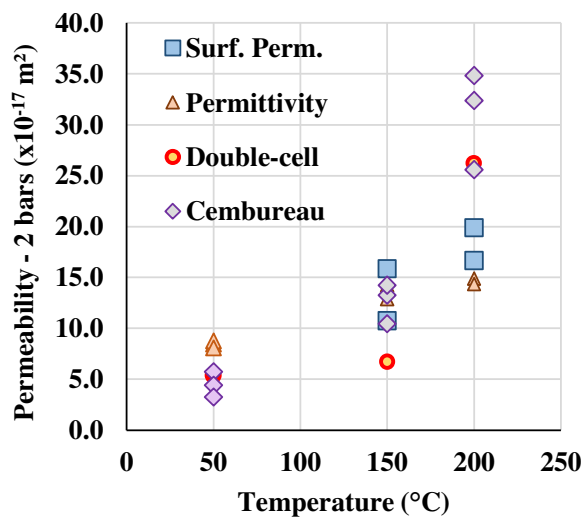
	Slab	B2-10	B3-10	B2-9	B3-9
Temperature	°C	150	150	200	200
Surf. Perm.	$\times 10^{-17} m^2$	30.6	45.1	47.3	56.5
Permittivity	-	5.0	4.8	4.7	4.8
Deduc. Sr		5.1	2.9	1.8	2.6
Double-cell	$\times 10^{-17} m^2$	11.8		46.0	

611

612 Apparent permeability was then evaluated as described previously and represented in Figure
 613 14. At 150 °C, the evaluation given by surface permeability and permittivity was in good
 614 accordance and consistent with the Cembureau measurement. When compared to the direct
 615 measurement performed by double-cell, the three techniques overestimated the permeability.

616 At 200 °C, the evaluation performed with the three permeability techniques (surface
 617 measurement, double-cell and Cembureau technique on samples) were quite scattered but
 618 centred on the value determined by double-cell. The permittivity did not show significant
 619 evolution between the two loadings (150 °C and 200 °C) and underestimated the permeability.
 620 At the end of the thermo-hydric loading, the water content in the concrete was very low and
 621 permittivity measurement was not sensitive to the evolution of transfer paths.

622 For such conditions (thermo-hydric loading with exposure at 150 °C and 200 °C), concrete
 623 slabs should have been significantly damaged [52,53]. Cracking is a random phenomenon and
 624 can increase the usual heterogeneity of concrete. This can explain an increase of scatter on the
 625 measurements after loading leading to cracking. The dimensions of the surface permeameter
 626 (diameter of 40 mm for the measurement cell), designed first to evaluate permeability of the
 627 cover concrete, led to a limited representative volume during measurement. This can increase
 628 the impact of material heterogeneity on the permeability evaluation.



629

630 *Figure 14: Evaluation of apparent permeability at 2 bars with the different techniques on slabs after thermal*
 631 *hydric loading*

632 **3.3 Application to real structures: concrete permeability of Vercors mock-up**

633 *3.3.1 In situ measurements*

634 In this part, the three non-destructive techniques are applied to evaluate the permeability of
635 the concrete of the Vercors structure. This structure is the mock-up of a reactor containment at
636 1/3 scale. It was built by EDF to help with the management of the long-term operation of its
637 fleet of Nuclear Power Plants [19].

638 The aim was to compare the evaluation of the concrete permeability by three techniques that
639 can be used in the field. Eighty measurements were performed with the surface permeameter
640 and with the permittivity technique in the same locations of the structure on two horizontal
641 lines around the mock-up and three vertical lines representative of the mock-up (Figure 15).
642 These measurements were taken after the usual exposure of the surfaces of the mock-up to
643 water performed during each enclosure test in order to detect singular air flow. This is an
644 important point as it can impact the experimental results. Before the water sprinkling, skin
645 concrete was sufficiently dry to prevent resistivity from being measured for most of the
646 measurement locations. After sprinkling, some resistivity measurements were made in 27
647 locations, but, as shown in the following part, most of the measurements were higher than 300
648 $\Omega.m$ and, thus, in a domain where the results are usually quite scattered (Figure 9) and not
649 very precise.

650

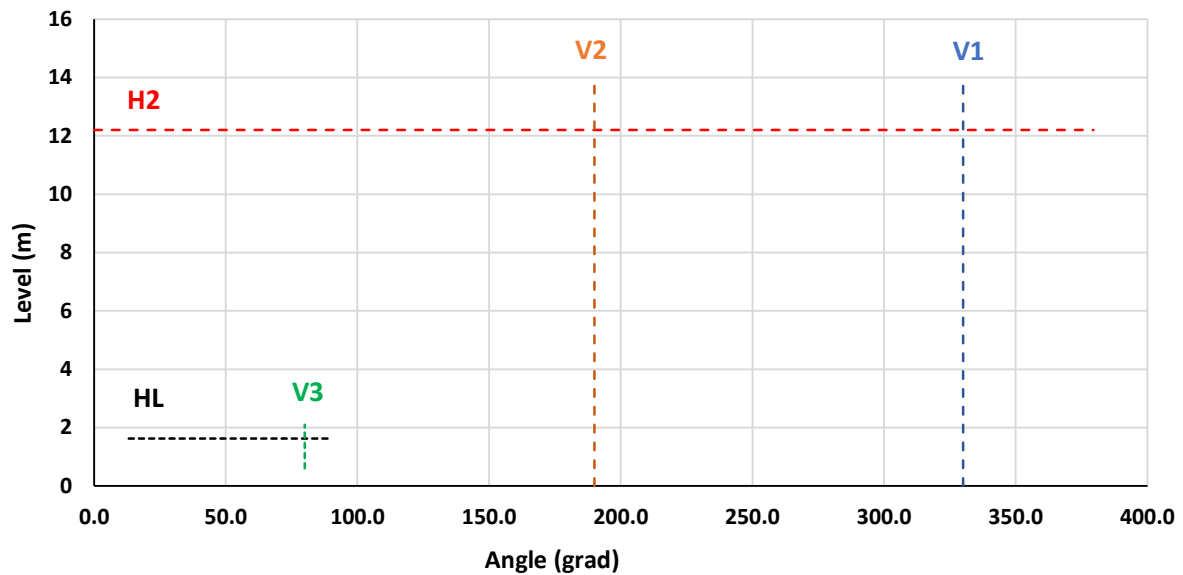


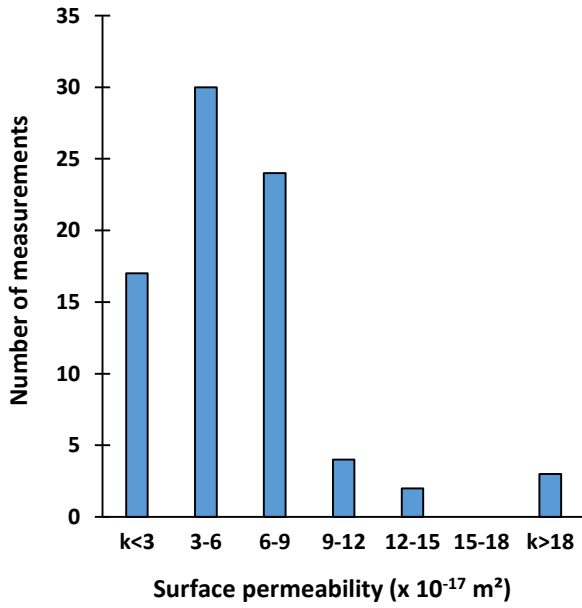
Figure 15: Locations of the measurements points along two horizontal and three vertical lines of the mock-up

651

652 As the mock-up has been realized for engineering and research work, particular attention was
 653 given to obtain the same reproducible material during the construction. All the measurements
 654 performed in this paper were located on the same face of the containment and protected from
 655 direct rain by the external wall and by the dome. Thus, the reasons for the discrepancy due to
 656 location of measurement were limited in this application.

657 Figure 16, Figure 17 and Figure 18 represent the distributions of surface permeability,
 658 permittivity and resistivity, respectively, measured on the mock-up. It has been chosen to
 659 present first the measurement results as histograms. This makes it possible to have a global
 660 view of the results and to estimate that the discrepancy stays quite small even if different
 661 castings were realized. These data can also be helpful for researchers interested in
 662 probabilistic approaches. In the following part, the permeability deduced from these
 663 measurements is presented by distribution along the five measurements lines to evaluate the
 664 discrepancy according to measurement location.

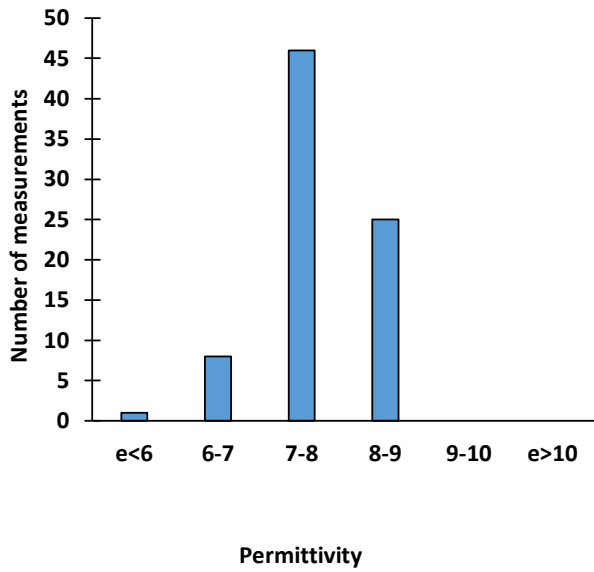
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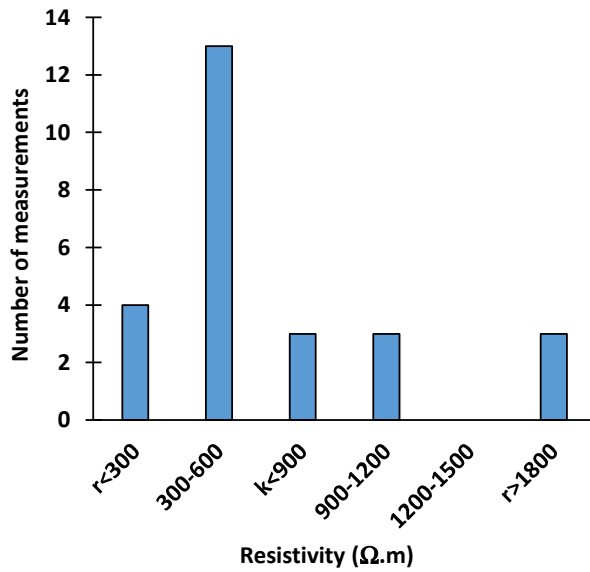
667 *Figure 16: Measurement of surface permeability on mock-up (80 values – mean: $5.9 \times 10^{-17} \text{ m}^2$, min: $0.41 \times 10^{-17} \text{ m}^2$, max $27.6 \times 10^{-17} \text{ m}^2$)*

668



669

670 *Figure 17: Measurement of permittivity on mock-up (80 values – mean: 7.70, min: 5.60, max: 8.73)*



671

672 *Figure 18: Measurement of resistivity on mock-up (27 values – mean: 970 Ω.m, min: 233 Ω.m, max: 5471 Ω.m)*

673 *3.3.2 Evaluation of the saturation degree*

674 Permittivity and resistivity were used first to evaluate the saturation degree (Table 6). From
 675 the calibration performed on the samples, the saturation degree evaluated by permittivity on
 676 the mock-up lay between 12% and 42%, with a mean value of about 31.5% for the 80
 677 measurement points, while resistivity gave a mean saturation degree of about 42.6% on 27
 678 measurement points. The mean saturation degree evaluated by the permittivity on the same 27
 679 points was about 29.8%. Thus, the difference of results is not a problem of the locations of the
 680 measurement points but really a difference between the responses of the two techniques.

681 *Table 6: Saturation degree deduced from permittivity and resistivity*

	By permittivity	By resistivity
Min	12.1	17.3
Mean	31.6	42.6
Max	41.9	60.1
N° of values	80	27

682

683 The surface permeability can also give interesting information about the saturation degree.

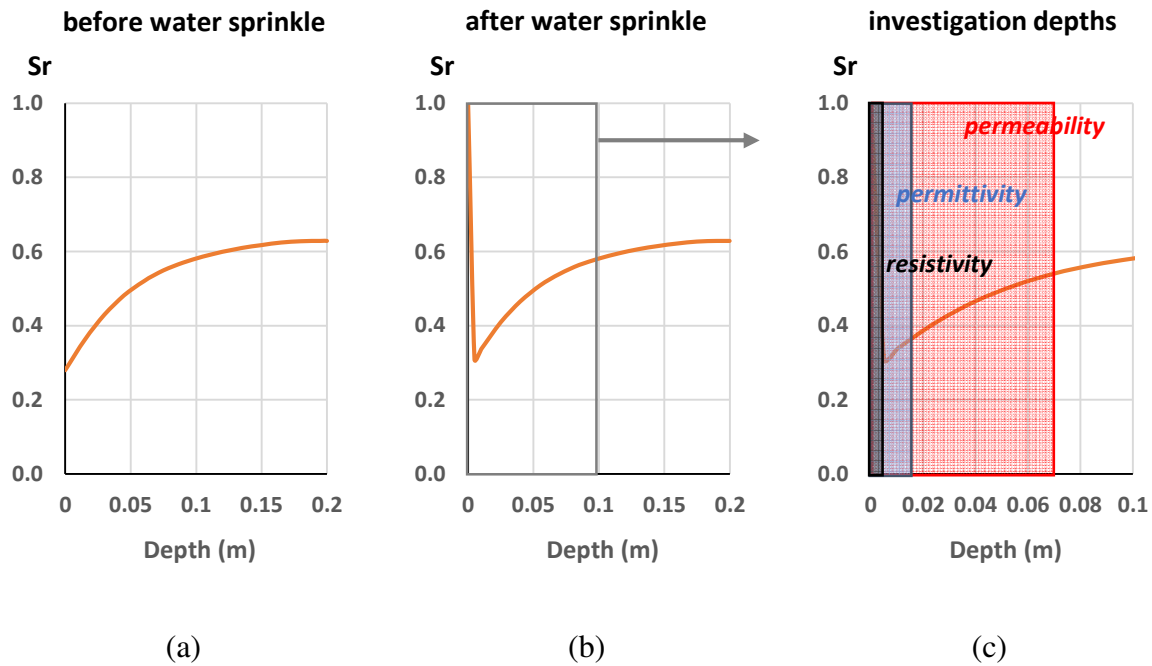
684 With this aim in mind, the mean increase of pressure, \dot{P}_c , was evaluated for the 80

685 measurements performed on the mock-up and compared to the measurements performed on

686 laboratory samples. The mean \dot{P}_c was equal to 2.2, which corresponds to a concrete saturated
687 at about 40% of saturation for the laboratory samples.

688 Resistivity measurement was very sensitive to the saturation [12,13,17,18]. Below 40% of
689 saturation, the continuity of the solution in concrete porosity was not sufficient to give a
690 reliable response. For dry concrete with small saturation (lower than 40%), permittivity
691 presents more precise results, because the measurement does not depend on the continuity of
692 the solution but only on the water content. The tests were performed during an enclosure test
693 and, thus, just after the water sprinkling of the concrete surface, water saturated a small
694 thickness of concrete (probably some millimetres – Figure 19). It was just enough to have a
695 superficial continuity of the concrete solution and thus to measure the resistivity. In this
696 situation, the measurement probably represents the saturation of only the first few millimetres
697 of the concrete skin. Permittivity is not influenced by the continuity of measurement. With the
698 apparatus used in this work, permittivity was measured over about 15 mm of depth (Figure
699 19). As the water due to the sprinkling did not have time to penetrate the concrete, the
700 saturation degree given by the permittivity was smaller but representative of a larger thickness
701 of concrete. Finally, the measurement of surface permeability investigated thicknesses lying
702 between 50 and 100 mm. For such thicknesses, the technique integrates the saturation degree
703 of the skin and also the saturation degree of deeper concrete, for which the saturation degree
704 is higher (Figure 19).

705



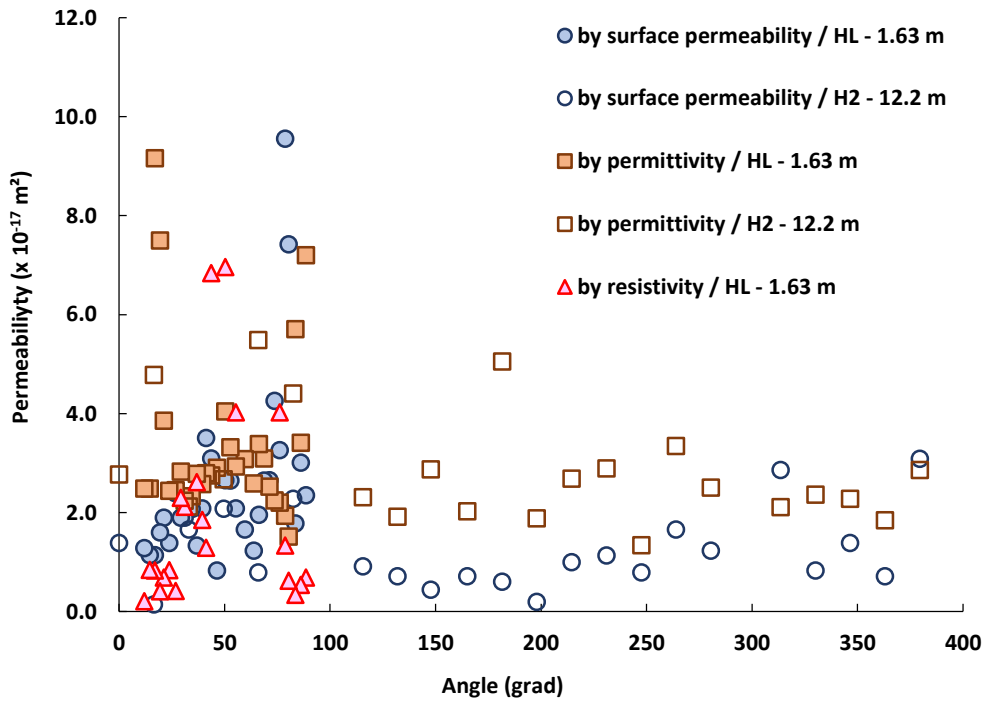
706 *Figure 19: Gradient of water content of a half depth of the mock-up wall (total depth: 0.4 m) before water*
 707 *sprinkling [20] (a), approximate gradient after water sprinkling (b), and approximate depths of investigation for*
 708 *the three techniques (c)*

709

710 3.3.3 Evaluation of apparent permeability

711 Then, the concrete apparent permeability for an absolute pressure of 2 bars was evaluated
 712 from the measurements obtained with the three techniques. The permeability deduced from
 713 the three techniques is presented along the two horizontal lines (Figure 20) and the three
 714 vertical lines (Figure 21). Minimum, mean and maximum values of this evaluation are given
 715 in Table 7.

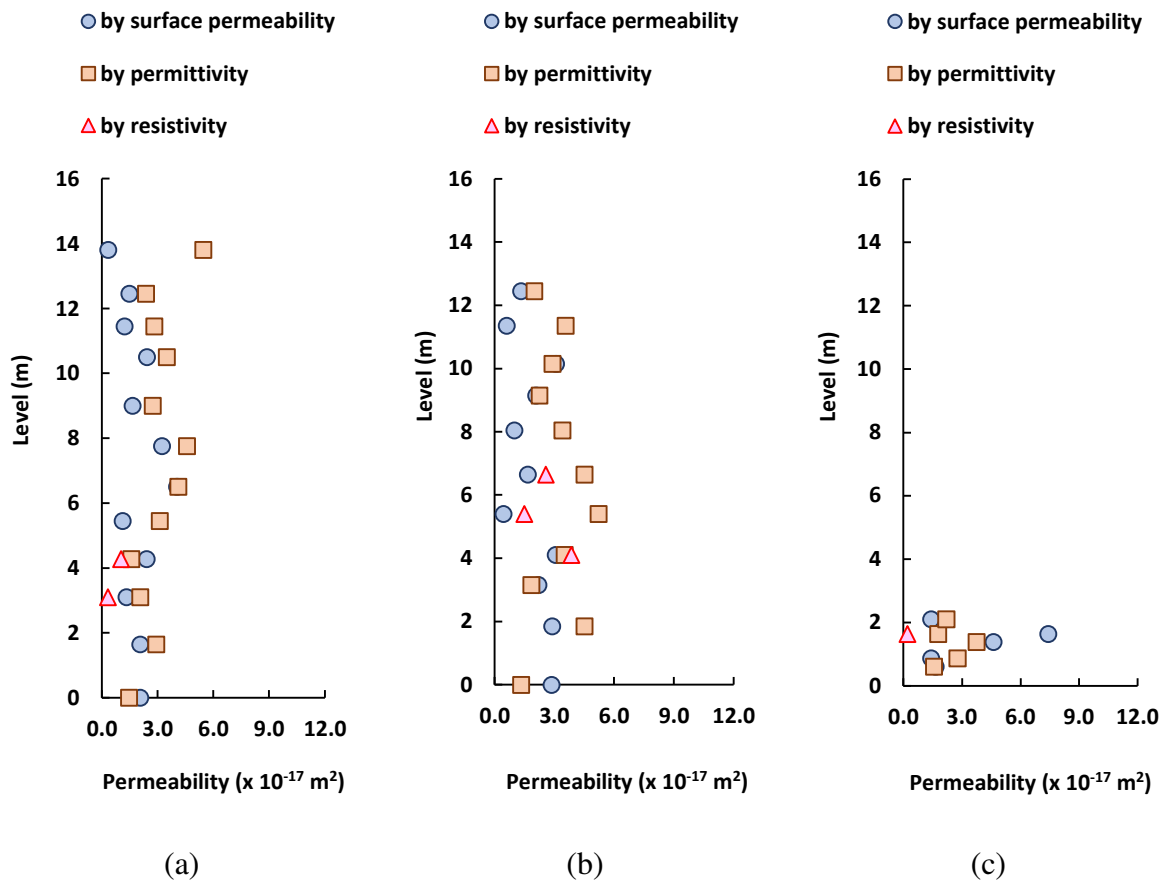
716



717

718 *Figure 20: Distribution of the permeability deduced from surface permeameter, permittivity and resistivity*
 719 *measurements along the two horizontal lines*

720



721 *Figure 21: Distribution of the permeability deduced from surface permeameter, permittivity and resistivity*
 722 *measurements along the three vertical lines (a: V1, b: V2 and c: V3)*

723

724 *Table 7: Apparent permeability of the mock-up concrete evaluated by a surface permeameter, permittivity and*
 725 *resistivity (x 10⁻¹⁷ m²)*

	By surf. perm.	By permittivity	By resistivity
min	0.14	1.33	0.21
mean	2.06	3.1	1.7
max	9.55	9.16	6.96
N° of values	80	80	27

726

727 Figure 20, Figure 21 and Table 7 highlight the difference in the evaluation of the permeability
 728 by the three techniques.

729 With all the measurements, the surface permeability led to a mean apparent permeability of
 730 about 2.06 x 10⁻¹⁷ m². Three points presented very large permeability (higher than 6. x 10⁻¹⁷
 731 m²). The two highest values were located on the horizontal line close to the angle 80 grad and

732 thus close to a rib for prestressing anchorages. They indicate a zone with poor transfer
733 resistance. This is consistent with permittivity measurement which shows a small saturation
734 degree in this part of the mock-up. The evaluation performed from the permittivity
735 measurements led to greater values of permeability in most of the measurement points. The
736 results were consistent with the results in the laboratory: with saturation of about 30%, the
737 concrete permeability can be expected to be between 3 and $4 \times 10^{-17} \text{ m}^2$ (Figure 5). The two
738 highest values of permittivity were located on the horizontal line close to the angle 20 grad,
739 but the other measurements do not show extreme values in this zone. The distribution
740 obtained for the resistivity was mainly in the range of the smallest apparent permeability
741 obtained with the surface permeameter. The mean value for 27 points was about 1.73×10^{-17}
742 m^2 . The horizontal distribution of the permeability deduced from resistivity shows abrupt
743 variations with angle. It can be due to the limit observed in laboratory: for dry concrete,
744 resistivity is highly non-linear with the saturation degree and the dispersion of the
745 measurement increases.

746 Therefore, the mean values of apparent permeability given by the three techniques were quite
747 close: the permittivity predicted an apparent permeability 35% greater than the surface
748 permeameter and the resistivity gave a permeability 25% smaller than the permeameter
749 technique. As discussed in the previous section, the differences may have come from the
750 depth investigated by each technique (some millimetres of skin due to water sprinkling for
751 resistivity, about 15 mm for the permittivity and more than 50 mm for the permeameter -
752 Figure 18).

753 **4 Discussion**

754 The work of the first step on laboratory specimens, confirmed the interest of three non-
755 destructive techniques (surface permeameter, permittivity, resistivity) for the evaluation of the
756 air permeability and saturation degree of concrete. Permittivity and resistivity depend on the

757 water content of the concrete and can thus be useful to evaluate the saturation degree [54,55].
758 Such an evaluation combined with van Genuchten's law, calibrated on laboratory specimens
759 by the Cembureau technique, allows the indirect evaluation of air permeability of concrete in
760 the field. In the second step, on laboratory slabs, the three techniques were used in the
761 laboratory for slabs of large dimensions and were compared with direct measurements of
762 permeability developed especially for this programme. In spite of some discrepancies, the
763 comparative analysis highlighted the consistent results for the different techniques. The third
764 step aimed to use the three techniques on a mock-up of a reactor containment at 1/3 scale. As
765 the measurements were made after exposure of the surfaces of the mock-up to water to detect
766 singular air flow during the enclosure test, the conditions of moisture according to concrete
767 depth were not in equilibrium with external conditions and the concrete skin presented a
768 strong humidity gradient (Figure 18). This is an important difference with investigations on
769 slabs, which were set up to have conditions that were as homogeneous as possible. It is
770 important to note that each technique investigates different depths of concrete. The
771 combination between moisture gradient and difference of investigation depth can partly
772 explain the small differences between the mean apparent permeability obtained with the three
773 techniques.

774 The problem of investigated depth is important to perform relevant expertise. In a massive
775 structure, water content is not homogeneous. Important moisture gradients exist between the
776 core and the skin. Close to the external limit, the saturation degree decreases abruptly.
777 Currently, no experimental technique is able to evaluate a gradient of moisture in the depth of
778 a concrete wall. Increasing the investigated depth would lead to average measurement results.
779 The result would not be more precise and would stay difficult to interpret without modelling.

780 In this mock-up, reinforcement bars were located at about 20 mm of the external skin. Steel
781 bars can disturb the results of electrical methods [56,57]. Thus, the equipment was chosen to
782 decrease the risk of disturbance by steel bars and to investigate less than 20 mm [58].
783 For such strategic structures, measurements cannot be the only way for expertise. They should
784 be combined with numerical modelling through global methodology to precisely evaluate the
785 moisture gradient through the wall [59,60]. In such approaches, the precise knowledge of the
786 moisture conditions, even at 10 mm depth, is very important to avoid assumptions which are
787 difficult to verify [60]. A few years ago, this type of evaluation required destructive sawing
788 techniques [59]. They led to a certain degradation of the structure which is not acceptable for
789 nuclear containment buildings. Resistivity for concrete exposed to high moisture conditions
790 and permittivity in most cases can lead to evaluate the water content close to concrete skin
791 without degradation of the concrete. It is an important improvement to control the boundary
792 conditions imposed in modelling.
793 Finally, air flow through structural concrete is the combination of diffuse flow through the
794 concrete and singular flow through preferential paths due to casting joints (caused by the
795 manufacturing of the mock-up in several stages) or cracks. The first objective of the surface
796 permeameter is to evaluate the diffuse flow, but it can also give interesting data to evaluate
797 small singular flows. These techniques allowed the apparent permeability of the concrete skin
798 to be evaluated. In the core of the concrete structure, the saturation degree is higher and the
799 flow through the enclosure vessel has to be evaluated with a realistic moisture gradient in the
800 wall.

801

802 **5 Conclusion**

803 The aims of this experimental work were to compare the response of three non-destructive
804 techniques to, directly or indirectly, evaluate the air permeability of concrete in containment
805 structures in laboratory and in field during the service life and after accidental conditions.

806 In laboratory conditions:

- 807 - For most of the situations, the three techniques of permeability measurement based on
808 an air flow evaluation (global measurement with double cell, evaluation on
809 representative specimens by Cembureau, and surface permeameter) were in good
810 agreement with respect to concrete heterogeneity (most differences are less than 50%).
811 The double cell technique is of great interest to evaluate the permeability in steady
812 state for elements of large size. It has thus been shown that the apparent pressure for
813 an absolute pressure of 2 bars can be evaluated from surface permeability measured in
814 vacuum.
- 815 - Both electrical measurement techniques (permittivity and resistivity) give consistent
816 values of concrete saturation degrees for values above 60% RH but are strongly
817 dependent on this saturation, especially near this value. Under 60%, resistivity shows
818 high dispersion and particular attention should be paid to the analysis of this
819 measurement for concrete under such conditions. Permittivity can be used for all
820 ranges of saturation, from totally saturated to dry concrete. Under 20% of saturation,
821 this technique seemed to be more sensitive to small changes in the concrete or in the
822 environmental conditions during tests. Meanwhile such degree of saturation is rarely
823 encountered for real reinforced concrete structures in normal conditions of service.
- 824 - The prediction of permeability by the two electrical techniques can lead to great
825 scattering due to the accumulation of uncertainties when their measurements were
826 combined with van Genuchten's law evaluated with the Cembureau technique on

827 specimens. The scattering can be explained by the sensitivity of the techniques to
828 saturation degree and by the high nonlinearity of concrete permeability with the
829 saturation degree.

830 - Accidental conditions led to very low saturation degrees in concrete slabs. Resistivity
831 could not be used and permittivity was no more so precise. Surface permeameter
832 underestimated the permeability compared to double cell technique. It can be due to an
833 increase of heterogeneity due to cracking induced by the thermal loading.

834 For the use on a mock-up of a reactor containment at 1/3 scale:

835 - Surface permeameter gave a precise mapping of the distribution of permeability along
836 two horizontal and three vertical lines. The transfer property was quite homogeneous
837 in the structure except close to a singularity (presence of prestressing anchorages).

838 - The concrete skin presented a strong humidity gradient (Figure 18). However, from
839 the saturation degree evaluated with permittivity and resistivity, it was possible to
840 evaluate the apparent permeability of concrete skin by means of a van Genuchten law
841 calibrated in the laboratory on representative samples of the structural concrete. This
842 method gave interesting results on the mock-up when compared to the surface
843 permeability measurements.

844 - The combination of these two non-destructive electrical techniques with a surface
845 permeameter helps to provide a better understanding of the saturation state of the
846 concrete in the field. However, for accurate measurements of concrete permeability in
847 field, the present work highlights the need to use a surface permeameter. Electrical
848 techniques lead to correct evaluation of the degree of saturation in field. But the
849 accumulation of uncertainties can lead to large scattering for the prediction of the
850 permeability by such techniques especially close to their domain of use.

851 - Even if the saturation degree can only be measured for small investigated depth with
852 resistivity and permittivity, it is a crucial data to help modelling to have realistic
853 boundary conditions for calculations of moisture transfer in concrete structures.

854

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