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Impact of reinforcement-concrete interfaces and cracking on gas transfer in concrete

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Abstract: The durability of reinforced concrete structures is largely impacted by their transfer properties, which can be evaluated through, for example, permeability measurement. Usually, concrete permeability is studied on plain specimens and the effect of the presence of steel bars on permeability in reinforced concrete has been little studied in the literature. The steel-concrete interface presents a larger porosity than plain concrete, which can be the cause of preferential percolation paths for fluids. Such percolation paths could create a lower resistance to fluid transfer and modify transfer kinetics. For reinforced and prestressed structures with large reinforcement contents, such as found in nuclear power plants, the impact of the reinforcement on gas transfer should be identified to obtain a better assessment of the flow within the structure. The aim of this experimental study is to characterize the effect of the presence of reinforcement on such flows by measuring leakage rates, permeability, and time to reach the steady state. Measurements were performed with a Cembureau constant head permeameter on cylindrical concrete specimens with or without steel bars. Since gas transfer into concrete depends on the rate of saturation of the material, the specimens were tested at different degrees of saturation: 0%, 6%, 30%, 60%, 80%, 90% and 100%. The analysis quantifies the impact of the defects created by the steel bar for each state. The results show that material composed of concrete and reinforcement can be divided into two distinct permeability zones: the plain concrete and the steel-concrete interface with or without cracking. These two zones can be associated in series and/or in parallel according to the configuration. The consequences on permeability measurement in reinforced structures are discussed.

Keywords: Reinforced concrete, durability, transfer, gas permeability, crack.

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29 **Highlights:**

- 30 - Permeability were measured on reinforced samples for different saturation degrees,
- 31 - Steel bars embedded in concrete lead to an increase in the sample permeability,
- 32 - For high saturation degrees, the steel-concrete interface is the main transfer path,
- 33 - Cracking induced by the restrained shrinkage participate to transfer,
- 34 - Equivalent defect opening can quantify the impact of the interface on air transfer.

35

36 **1. Introduction**

37 The penetration of aggressive agents, water, chloride and other ionic species into concrete is
38 responsible for most of its deterioration [1]–[3]. The viability of many structures depends on their
39 concrete transport properties [4]–[6]. The permeability of a reinforced concrete and the extent to
40 which it permits diffusion are considered as major indicators of its durability [3], [5], [7]. Fluid
41 transport in a porous material is possible because of the presence of paths of connected porosity. In
42 concrete, the pathways are mainly: the capillary pores of the cement paste [7]–[9]; the interfacial
43 transition zone between cement paste and aggregate [8], [10]–[12]; and micro cracks in aggregates
44 and cement matrix [8], [13]. Most of the research on the subject has dealt with plain concrete and
45 mortar without reinforcement, so the effect of the presence of steel bars on the permeability of
46 reinforced concrete has been little studied. Reinforcements lead to obtain smaller cracks opening
47 for concrete under mechanical loading and thus to decrease permeability in damaged concrete [14]–
48 [17]. This impact of reinforcement has to be taken into account for leakage prediction in real
49 structures [18]. The inclusion of fibres decreases permeability properties in concrete with [19], [20]
50 or without [21] cracks due to mechanical loading. Previous experimental works analysed the
51 mechanical role of reinforcement on the permeability of loaded concrete. In this case, several
52 mechanisms impact concrete permeability: the modification of porosity due to mechanical loading,
53 the cracks occurrence and the impact of the steel-concrete interface. Small stresses lead to
54 compaction and thus to the decrease of permeability [25] and permeability increases when cracks
55 connectivity occurs [25], [26]. In reinforced concrete samples, steels densify the cracking and reduce
56 the crack width due to loading. Reinforcement leads to a reduction of the flow through cracks and
57 thus of the permeability.

58 However, reinforcement bars are also responsible for concrete cracking due to restrained shrinkage,
59 even without external loading. The induced cracks and also the voids at the interface with the
60 concrete [22]–[24] disturb the transfers in concrete, particularly close to the skin, where transfer has
61 a preponderant effect on durability. For reinforced concrete submitted to loading, the different
62 mechanisms acting on permeability are concomitant. To obtain precise modelling, it is necessary to
63 distinguish the part of each mechanism: the impacts of the mechanical loading, of the induced cracks
64 and of the steel-concrete interface. As a consequence, transfers in plain and reinforced specimens
65 without mechanical loading have to be analysed to assess the capacity of steel-concrete interfaces
66 to provide gas transfer paths.

67
68 If the steel-concrete interfaces are actually preferential paths of transfer and become accessible to
69 fluids from the surface through cracking, the reinforcement cover would become unable to assume

70 its protective role against aggression and so the steel bars could be directly exposed. The degradation
71 kinetics of reinforced concrete becomes greatly accelerated if other phenomena do not occur
72 (healing, precipitation). Similarly, as these steel-concrete interfaces act on the kinetics of the fluid
73 flow, they can change the time necessary to reach the steady state of flow due to their low resistance
74 to transfer [27], according to the design of the reinforcement in the structure. In heavily reinforced
75 structures, the steel-concrete interfaces are numerous, have considerable area and are highly
76 connected. Therefore, they form significant pathways for transfers, which should be considered
77 when predicting the durability, and particularly the air tightness of such structures. This study
78 analyses the contribution of steel-concrete interfaces to gas transfer within reinforced concrete.

79
80 The degree of saturation of concrete on site is usually very high close to water supply and in
81 locations submitted to rainfall and is usually over 80% at 50 mm depth [28], which prevents most
82 of the transfer in plain concrete. However, the Kelvin Laplace equation indicates that cracks with
83 an opening greater than one micrometre are drained even at high relative humidity (99.99%). So, in
84 the presence of skin cracking, the steel-concrete interface can easily be drained even if the saturation
85 level of the rest of the concrete is high. Since the permeability of concrete is affected by its water
86 saturation [5], [29]–[32], it is important to perform this study on material at different states of water
87 saturation.

88 **2. Objectives**

89 The objective of this paper is to analyse the impact of the steel-concrete interfaces on reinforced
90 concrete permeability, by inducing pathways for gas transport into concrete. They can change the
91 transfer kinetics and the time to reach steady state during a measurement of gas leak rate and can
92 thus constitute weak zones regarding the air tightness of reinforced concrete structures. Three
93 specific points are particularly highlighted:

- 94 - Impact of the steel-concrete interface on permeability,
- 95 - Impact of the steel-concrete interface on flow kinetics,
- 96 - Impact of induced cracking close to the steel-concrete interface on permeability.

97 The first two points will lead us to identify the different zones of permeability in reinforced concrete,
98 including the steel-concrete interface and induced cracking. The third point concerns an analysis of
99 the impact of the crack opening on the transfer. To obtain a more relevant identification and
100 characterization of the variation of permeability with the length of the steel-concrete interfaces in
101 site conditions, all three studies were performed for various states of saturation.

102

103 3. Theoretical background

104 Permeability is defined as the ability of a material to allow fluids to pass through it under a pressure
105 gradient. This property governs the flow rate of a fluid through a porous medium. The coefficient
106 of permeability k_a is defined by Darcy's law.

107 For the sake of simplicity, the “coefficient of permeability” is referred to simply as “permeability”
108 in this article unless otherwise noted. The gas permeability of a porous solid is calculated using the
109 Hagen-Poiseuille relationship for laminar flow of a compressible fluid through a porous medium
110 with small capillaries under steady-state conditions. The relationship solved for the apparent
111 permeability k_a can be written as in Eq. 1 [33].

$$112 \quad k_a = \frac{2 \mu L Q_O}{S} \frac{P_O}{P_I^2 - P_O^2} \quad (\text{Eq. 1})$$

113 where Q_O is the volume flow rate of the fluid (m^3/s), S is the cross-sectional area of the
114 specimen (m^2), L is the thickness of the specimen in the direction of flow (m), μ is the dynamic
115 viscosity of the fluid at the test temperature (Pa.s), P_I is the absolute inlet pressure (Pa), and
116 P_O is the outlet pressure (the pressure at which the volume flow rate is determined, assumed
117 in this test to be equal to atmospheric pressure – N m^{-2}).

118 For dried air at a temperature of 20°C , the dynamic viscosity μ may be taken as 1.83e^{-5} Pa.s.

119 4. Materials and methodology

120 4.1. Experimental setup

121 The permeability of porous materials can be evaluated through a gas flow measurement using a
122 permeameter with constant head (the difference in pressure is fixed during the measurement) or
123 variable head. In this study, a constant head permeameter was used. The apparatus is known as a
124 Cembureau permeameter. The permeating medium was dried air. Fig. 1 gives an overview of the
125 apparatus. The main elements are: an air supply cylinder fitted with a pressure reducing valve, a
126 precision pressure regulator, a pressure gauge, the permeability cell, a flow meter and a computer
127 to record the air flow.

128 In order to reach a precision of 1% in the determination of permeability, Kollek's specifications [33]
129 were followed: the inlet pressure, P_I , to the cell was controlled over a range of absolute pressure
130 from 2 to 5 bars (2×10^5 to 5×10^5 N.m^{-2}) by the pressure regulator and the set pressure level was
131 maintained within 1% of the selected pressure during the whole time of air flow measurement. The
132 graduations on the pressure gauge were 5×10^{-2} bars (5×10^3 N.m^{-2}). The permeability cells were

133 sealed by a tightly fitting polyurethane rubber joint under a pressure of 8 bars (1.5 times the
 134 maximum inlet pressure) against the curved surface. So a pressure difference of up to 4 bars (4 x
 135 10^5 N.m^{-2}) could be applied to the specimens in the permeability cells.
 136

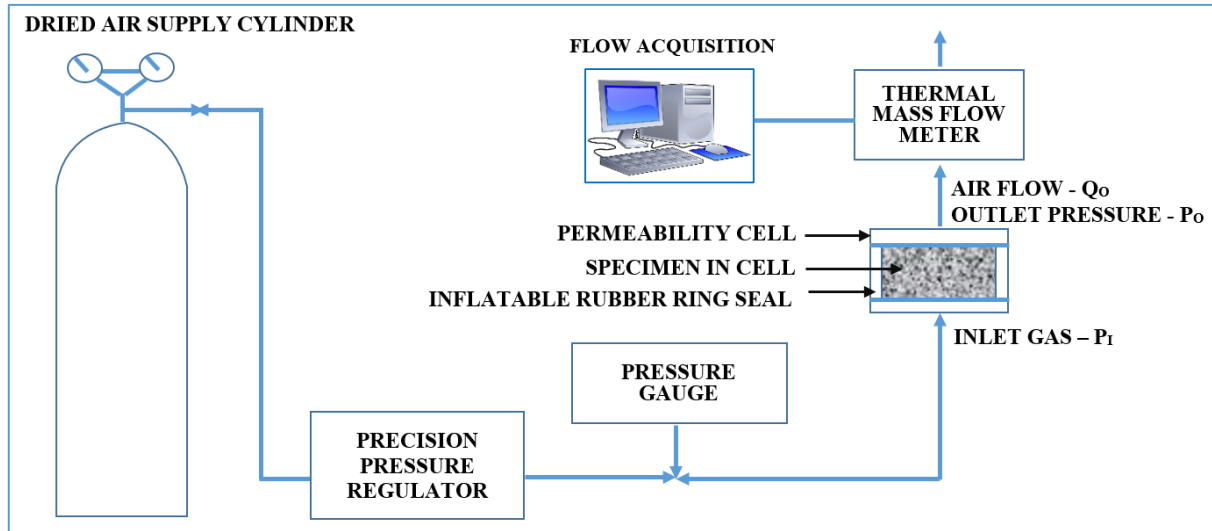


Fig. 1: Experimental apparatus

137 The air flow was recorded every 15 seconds by the digital thermal mass flowmeter (Brooks
 138 Instrument Hatfield PA 19440 USA, Brooks S/N: F23889 008 Model: 0254AB2B11A) to determine
 139 the air flow rate through the specimens with reliable accuracy. Two flowmeters were used according
 140 to the flow range: the first one for flows lying between 0 and 10 cm³/min and the second one for
 141 flow between 10 and 100 cm³/min. After initiating the percolation of dried air through the specimen
 142 at a given applied pressure, sufficient time was allowed for steady state flow to become established.
 143 The steady state condition was verified with the curves of air flow versus time. In this study, the
 144 time to reach steady state (TRSS) was short due to the transfer thickness (50 mm) [34]. The
 145 measurement allowed the TRSS to be compared among test configurations (comparison of the
 146 impact of steel bar length in concrete on TRSS) by direct comparison of the downstream flow. After
 147 having measured the flow in the steady state, the permeability k_a was calculated from the Hagen-
 148 Poiseuille equation for laminar flow of a compressible fluid through a porous body under steady
 149 state conditions (Eq. 1).
 150

151 **4.2. Experimental program**

152 Different configurations can be used to measure the air flow through reinforced concrete specimens.
 153 The transfer into the accessible pores and/or into cracks of the material can be analysed with the
 154 specimen configuration illustrated in Fig. 2. In this arrangement, the concrete around the

155 reinforcement and/or the crack openings directly governs the measured air flow and the contribution
 156 of the steel-concrete interface to the outlet flow, Q_o , cannot be isolated.

157

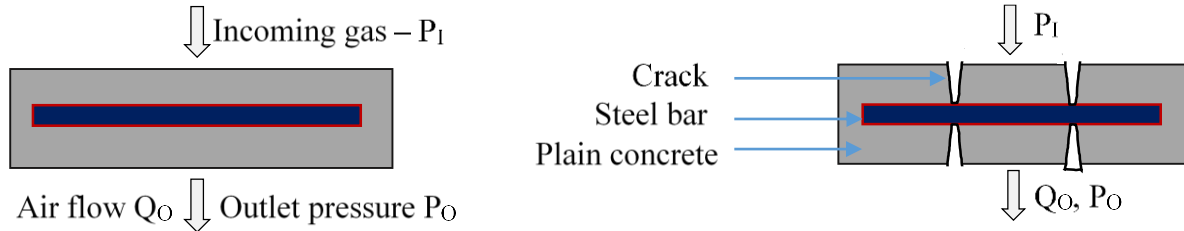


Fig. 2: Reinforced concrete for Q_o measurement: case n°1

158

159 On site, the steel-concrete interfaces can be directly or partially accessible to aggressive agents,
 160 particularly because of the presence of cracks induced, for example, by drying shrinkage or by
 161 external loading. An appropriate test setup for characterizing the impact of the steel-concrete
 162 interfaces would directly expose the steel-concrete interfaces to the inlet pressure as shown in Fig.

163 3.

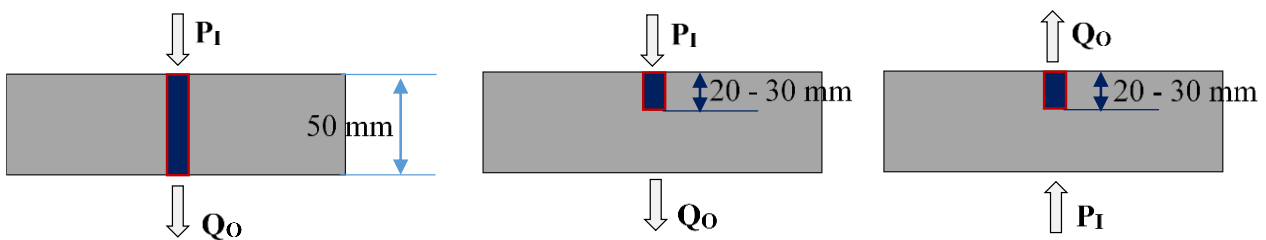


Fig. 3 Reinforced concrete for Q_o measurement in this study: case n°2

166

167 During the programme, four types of sample were tested (Fig. 4):

- 168 - Plain samples (P),
- 169 - Reinforced concrete with steel bar length of 20 mm (R2),
- 170 - Reinforced concrete with steel bar length of 30 mm (R3),
- 171 - Reinforced concrete with steel bar crossing the sample from face to face (length of 50 mm,
 172 R5).

173 The lengths of the reinforced bars in the samples were chosen in accordance to the concrete
 174 aggregate size (16 mm). The impact of reinforcement on permeability was studied for different
 175 degrees of saturation: 0%, 6%, 30%, 60%, 80%, 90% and 100%. The degree of saturation is
 176 indicated at the beginning of the specimen reference when necessary (Fig. 4).

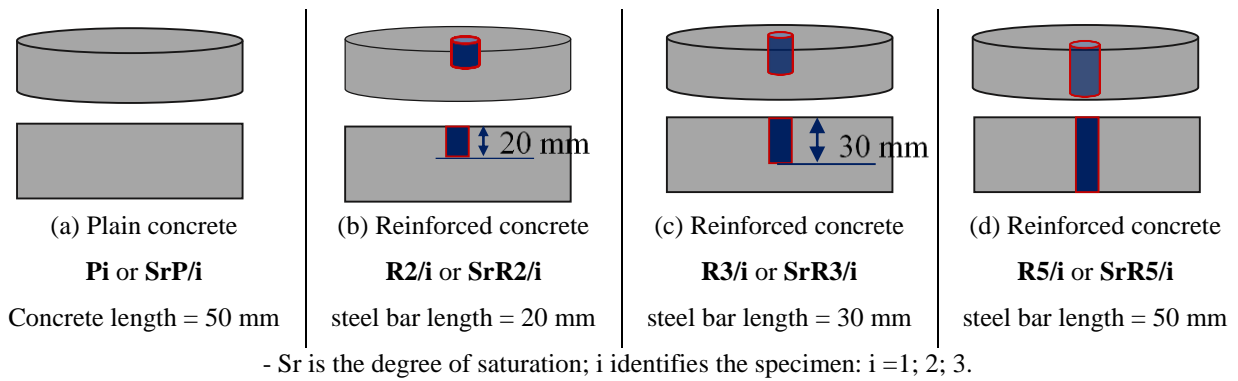


Fig. 4: Types and codes of specimens

179 4.3. Samples

180 To limit causes of scatter, all the samples were extracted from four cylindrical specimens with a
 181 diameter, ϕ , of 150 mm and height, h , of 200 mm: one specimen for the three plain samples (SrP/1,
 182 SrP/2, SrP/3) and three specimens for the reinforced concrete samples (SrR2/i, SrR3/i, SrR5/i) as
 183 shown in Fig. 5. All measurements were performed on three (3) samples of each type.

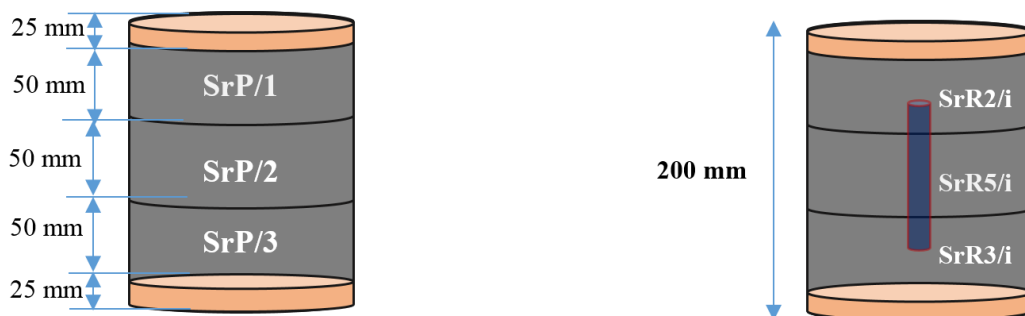


Fig. 5: Description of the samples SrP/i, SrR2/i, SrR3/i and SrR5/i

185 4.4. Concrete mix, casting, curing and preconditioning

186 Concrete mix is given in Table 1. Siliceous limestone aggregates were used. Silica contents of
 187 aggregates were about 80 and 5% for the sand and the gravels, respectively. Specimens ($\phi=150$ mm,
 188 $h=200$ mm) were cast in plastic moulds. Twenty-four hours after casting, they were removed from
 189 their moulds and cured in lime water at a temperature of 20 ± 2 °C for at least 60 days. This long
 190 time (60 days) in water was required to obtain a stabilized material regarding cement hydration [35].
 191 Lime water allows an increase of the pH and a limitation of carbonation and calcium leaching [36],
 192 [37]. After curing, the samples ($\phi=150$ mm, $h=50$ mm) were sawn from the original specimens and
 193 the first 25 mm of both sides were removed to avoid skin effects (Fig. 5). The samples were then

194 saturated with water under vacuum and dried to obtain the different water contents. The degrees of
195 saturation were calculated with the porosity obtained at the end of the drying process.

Table 1. Concrete mix for 1 m³

Constituents	[kg]
Sand 0/4 rec GSM LGP1	830
Gravel 4/11 R GSM LGP1	445
Gravel 8/16 R BALLOY	550
Cement CEM I 52.5 NCE CP2 NF	320
Plasticizer SIKAPLAST TECHNO 80	2.4
Water	213

196

197

Table 2. Preconditioning description

Sr (%)	Temperature (°C)	Drying time (day)	Cumulative mass loss (%)
90.	20.	0.8	0.8
80.	40.	1.	1.6
60.	50.	1.	3.1
30.	60.	5.	5.9
6.	60.	22.	7.8
0.	105.	2.	8.2

198

199 The preconditioning of the samples is described in Table 2. The specimens of concrete were dried
200 at four temperatures to reach the different degrees of saturation (Sr). They were first dried in an
201 oven at 40°C to achieve Sr equal to 80%, then at 50°C to reach Sr of 60%, then at 60°C to reach
202 30%, and again at 60°C to achieve the smallest saturation for this temperature (considered to have
203 been obtained when constant mass was reached, with a mass loss lower than 0.05% in 24 hours).
204 These three temperatures were used to decrease the risk of inducing thermal cracking associated
205 with drying at 105°C. If 105°C is considered as the reference temperature at which the degree of
206 saturation is assumed to reach zero, the specimen "dried" at 60°C actually contained an amount of
207 water corresponding an Sr of 6%. The saturation degree of 6% was studied to obtain the permeability
208 at the lowest saturation degree and to minimize the impact of thermal damage. Finally, to achieve a
209 fully dry state, samples were dried in an oven at 105°C until constant mass was reached (less than
210 0.1% change in mass in 24 hours). At each drying state, the samples were wrapped in aluminium
211 foil and put into the oven to allow the moisture to spread evenly in the material. The duration of

212 homogenization was at least equal to the drying time and the temperature was the same as during
 213 drying. The permeability test was performed after each drying stage. This preconditioning to ensure
 214 an identical material before and after drying was inspired by the literature [31], [38], [39]. For
 215 saturation at 90% and 100%, no oven drying was required. For the degree of saturation of 100%,
 216 permeability tests were performed directly at the end of the curing period in lime water. For 90%,
 217 samples were simply left in the test room at 20°C for 20 hours. The specimens were weighed before
 218 and after the permeability measurements. No variations were noted. Global degree of saturation was
 219 constant during the permeability measurement.

220

221 **4.5. Concrete properties**

222 Tables 2 presents the porosity of samples according to the configuration. The porosity accessible to
 223 water of each type of specimen and the apparent density of plain concrete are noted with the standard
 224 deviation. This porosity was determined according to the AFPC-AFREM method [40] on the
 225 complete sample including the steel bar.

226 The steel bars used were ribbed bars 14 mm in diameter. The ribbing of the steel surface was
 227 expected to increase adherence and reduce the voids along the steel-concrete interface.

228

Table 3. Concrete properties

Porosity P [%]	18.8 ± 0.1
Porosity R2 [%]	19.3 ± 0.3
Porosity R3 [%]	19.4 ± 0.2
Porosity R5 [%]	18.8 ± 0.2
Apparent volumetric mass, P [kg/m ³]	2107.3 ± 3.8

229

230 As shown in Table 2, the porosity was rather high and of the same order of magnitude for all the
 231 specimens. The presence of different volumes of steel within the samples could have changed the
 232 porosity. As steel bars are non-porous, with a good quality steel-concrete interface, the transition
 233 from P to R2 and R5 could have led to a decrease of porosity. Conversely, a poor quality steel-
 234 concrete interface could have led to increases in porosity between P and R5. In this study, no
 235 significant differences were observed and no conclusions can be drawn with respect to the interface
 236 quality.

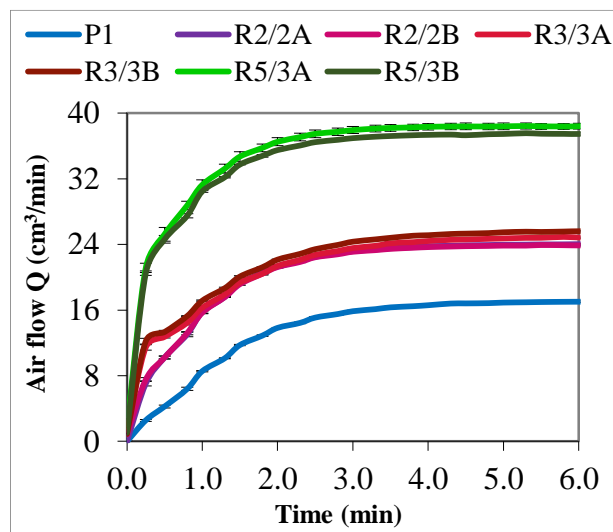
237

238 **5. Results**

239 **5.1. Reproducibility of the curves of air flow**

240 The steel-concrete interfaces and cracking resulting from restrained shrinkage around the
 241 reinforcement can be the origin of heterogeneities in reinforced concrete, which lead to differences
 242 in TRSS, so it was important to verify the reproducibility of flow measurements in the presence of
 243 reinforcement. For this purpose, each test was performed three times on one sample of each of the
 244 four configurations under study (Fig. 4). The results presented here were obtained on the samples
 245 in the driest state: 0P1, 0R2/2, 0R3/2 and 0R5/3. The samples were taken at random. Two
 246 reproducibility tests were performed: one related to measurements, starting from the same face, and
 247 one related to the impact of the choice of measurement face. The presence or absence of the steel
 248 bar on the face exposed to inlet pressure could have an impact on the measurement. The curves of
 249 air flow versus time $Q(t)$ are shown in Fig. 6.

250



251

252 **Fig. 6:** Air flow $Q(t)$ – two faces (A and B), tested at the saturation degree equal to 0% for the
 253 absolute pressure P_I equal to 2 bars (the curves corresponding to R2/2A and R2/2B coincide; the
 254 differences were lower than 0.3% of the scale)

255

256 **Table 4.** Maximum coefficients of variation for air flows obtained for 3 measurements on the
 257 same sample starting from a same face

(%)	P	R2	R3	R5
CoV	0.5	0.1	0.3	0.9

258

259 In all cases, the standard deviation for three measurements on the same sample was very low (less
260 than 1% – Table 4) and the measurement was reproducible with the presence of steel bars. The
261 volume flow rate and flow kinetics were the same whatever the face exposed to the inlet absolute
262 pressure (Fig. 6), even for asymmetrically reinforced samples (cases of R2 and R3 in which the steel
263 does not cross the sample completely). In the rest of the paper, no distinction will be made between
264 the faces subjected to the inlet pressure. The results presented here for one sample of each type are
265 representative of all the samples, even those made of reinforced concrete. Differences in amplitude
266 could be obtained among samples in the same configuration due to the heterogeneity created at the
267 interface by the reinforcement. It is important to note that all the curves of air flow obtained on the
268 reinforced samples can be divided into two parts (Fig. 6):

- 269 - an initial abrupt increase in flow. This jump is greater when the length of steel in the sample
270 is greater (R5 and R3),
- 271 - followed by the usual kinetics of fluid flow through plain concrete.

272 The plain samples showed no abrupt increase at the beginning but only the usual kinetics, as
273 expected.

274

275 The initial flow jump was due to the steel-concrete interface, which represented a defect regarding
276 the transfer of gas into reinforced concrete (discussion in section 5.3). It is important to mention that
277 this jump is not the same as the flow peak presented by Verdier and al. [34], which corresponds to
278 a measurement artefact due to the initiation of the inlet pressure and can be explained by the
279 evacuation of an outlet overpressure when inlet pressure is applied. To eliminate this parasite, the
280 pressure was always evacuated at the beginning of measurement by opening the valves at the outlet
281 of the permeability cell. Based on Verdier and al.'s work [34] and on the measurements performed
282 in the present work, fifteen seconds after application of the inlet pressure was enough to evacuate
283 this overpressure. The initial time (zero date) of the air flow measurement was taken from the
284 moment when this overpressure was evacuated.

285 The experimental results presented in Fig. 6 are in contrast with the measurements of porosity,
286 which did not show any significant differences (Table 3). The difference was due to a preferential
287 pathway of gas transport into reinforced samples that was not sufficiently significant to show an
288 impact on porosity but was revealed by flow measurements. This shows the good sensitivity of such
289 measurements for detecting small defects that can impact the concrete durability without significant
290 consequences on other properties. The highest permeability of the reinforced specimens (Fig. 7)
291 could be explained by the highest pore connectivity with the creation of preferential paths of gas
292 transfer into the concrete near the reinforcement or the steel-concrete interface. In the case of R5,

293 the path could be totally constituted by the steel-concrete interface, which opened out. In the case
 294 of R2 and R3, the presence of the steel bar could be the cause of cracking induced by drying in the
 295 concrete part under the steel bars. Such cracks were connected to the steel-concrete interface and
 296 could form a path between the two faces of the sample. The consequence was an increase in the air
 297 flow. The aggregate size had probably an impact on the connectivity of the pore network under the
 298 steel bars. Permeability measurement on samples with concrete thickness larger than 30 mm under
 299 the steel bar could exhibit a decrease of the initial flow jump.

300

301 5.2. Impact of steel-concrete interface on permeability

302 The permeability of samples was calculated from the flow rates in the steady state (Eq. 1). Fig. 7
 303 shows the evolution of apparent and relative permeability as a function of saturation. The inlet
 304 pressure was 2 bars. The results presented were similar at all test pressures (2, 3 and 4 bars).

305 As usual, the relative permeability was obtained from the ratio of the permeability at a given state
 306 of saturation and the permeability at saturation state $S_r = 6\%$: $k_{a,rel} = k_{a,S_r}/k_{a,S_r = 6\%}$. The state $S_r =$
 307 0% (drying of the material at 105°C) was not kept as the reference in order to limit the impact of
 308 damage due to this high temperature on the values of relative permeability. Average values and
 309 standard deviation were obtained from S_{rP1} , S_{rP2} , S_{rP3} (values in blue), $S_{rR5/1}$, $S_{rR5/2}$, $S_{rR5/3}$
 310 (green), $S_{rR2/1}$, $S_{rR2/2}$ (in purple), $S_{rR3/1}$, $S_{rR3/3}$ (red). Only the values of one sample ($S_{rR2/3}$)
 311 were not taken into account as the measured air flow was much too high – three hundred times
 312 greater than the other values – and so was not representative.

313

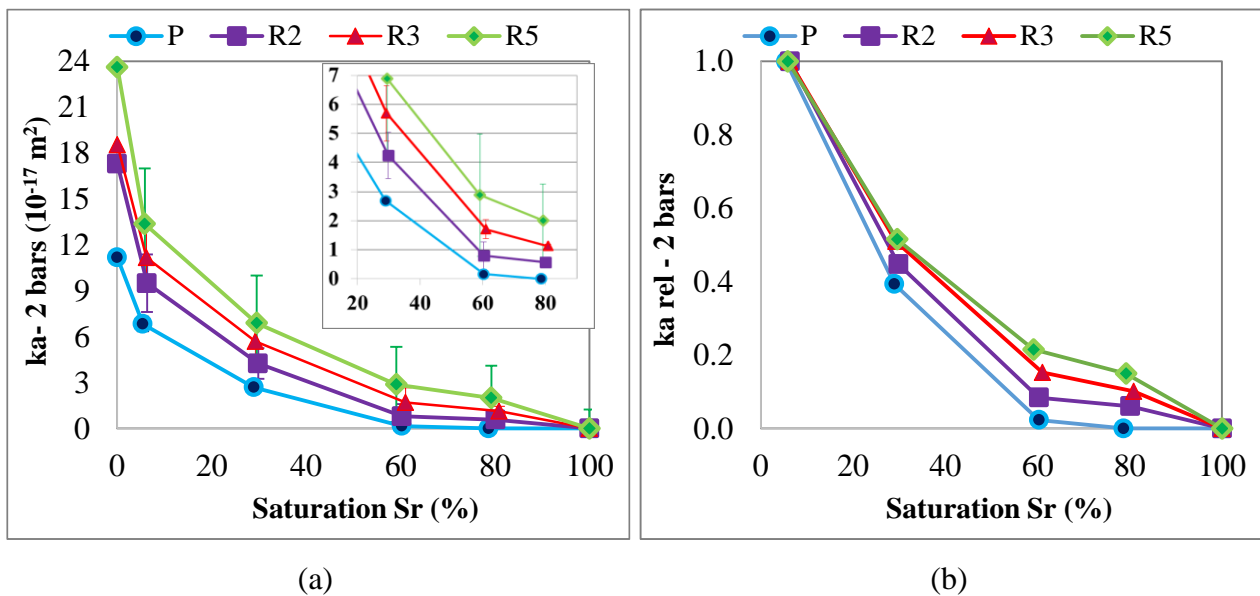


Fig. 7 : Apparent permeability (a) and relative permeability $k_{Sr}/k_{Sr = 6\%}$ (b) for $P_1 = 2 \text{ bars}$

314

315 Whatever the state of saturation, the permeability of plain concrete samples P was always the lowest
316 (Fig. 7). The presence of reinforcement led to significantly increase the permeability of samples.
317 The permeability of reinforced samples R5 (reinforcement crossing the sample) were the highest,
318 while the values of permeability obtained for R2 and R3 (steel not completely crossing the sample)
319 were intermediate. The zones with high permeability (preferential paths of gas transfer into the
320 concrete near the reinforcement or steel-concrete interfaces) were more noticeable at high
321 saturation. The presence of water in pores makes difficult the transfer of air in concrete. Air flow
322 decreases with the increase of concrete saturation [5], [32], [41], [42]. This phenomenon depends
323 on the geometry of the percolation path. Path with an opening greater than one micrometre can be
324 drained even at high relative humidity (99.99%). Thus, path formed by steel-concrete interface can
325 be drained more easily than usual concrete porosity. For S_r lying between 60% and 80%, all three
326 reference samples P were impermeable to air (low or zero permeability as obtained by many
327 researchers [5], [32], [41]) while all reinforced samples (R2, R3 and R5) were permeable (Fig. 7-b).
328 This means that the pathway formed by the interface and the cracks was larger and more connected
329 than the usual concrete pores. Consequently, they were desaturated even with the drying at 40°C,
330 while the rest of concrete was still in a high saturation state that did not allow gas transfer. At high
331 levels of saturation, such pathways had a greater impact on the gas transfer into the material.

332
333 Concerning the impact of the reinforcement, it is important to note the high standard deviation that
334 can be seen in the case of the reinforced samples completely crossed by steel bars while plain
335 concrete samples show little scatter (Fig. 7-a). This highlights the impact of the defect on flow paths.
336 These large standard deviations of the permeability of reinforced samples can be explained by the
337 heterogeneous nature of the steel-concrete interface [36], which can vary greatly from one sample
338 to another according to casting (vibration), drying, and difference in verticality of the steels in the
339 concrete during casting.

340
341 In summary, the analysis of the results presented in Fig. 7 leads us to break the downstream air flow
342 (from which the apparent permeability is calculated) down into two distinct contributions: one zone
343 of high permeability due to the "defect" caused by the presence of the steel/concrete interface and
344 induced cracking, and one zone of plain concrete. In all cases, the defect is located in the vicinity of
345 the steel. The impact is characterized by an initial jump in the measured air flow and leads to an
346 increase of the permeability of reinforced samples.

347
348

349 **5.3. Impact of steel-concrete interface on air flow and on flow kinetics**

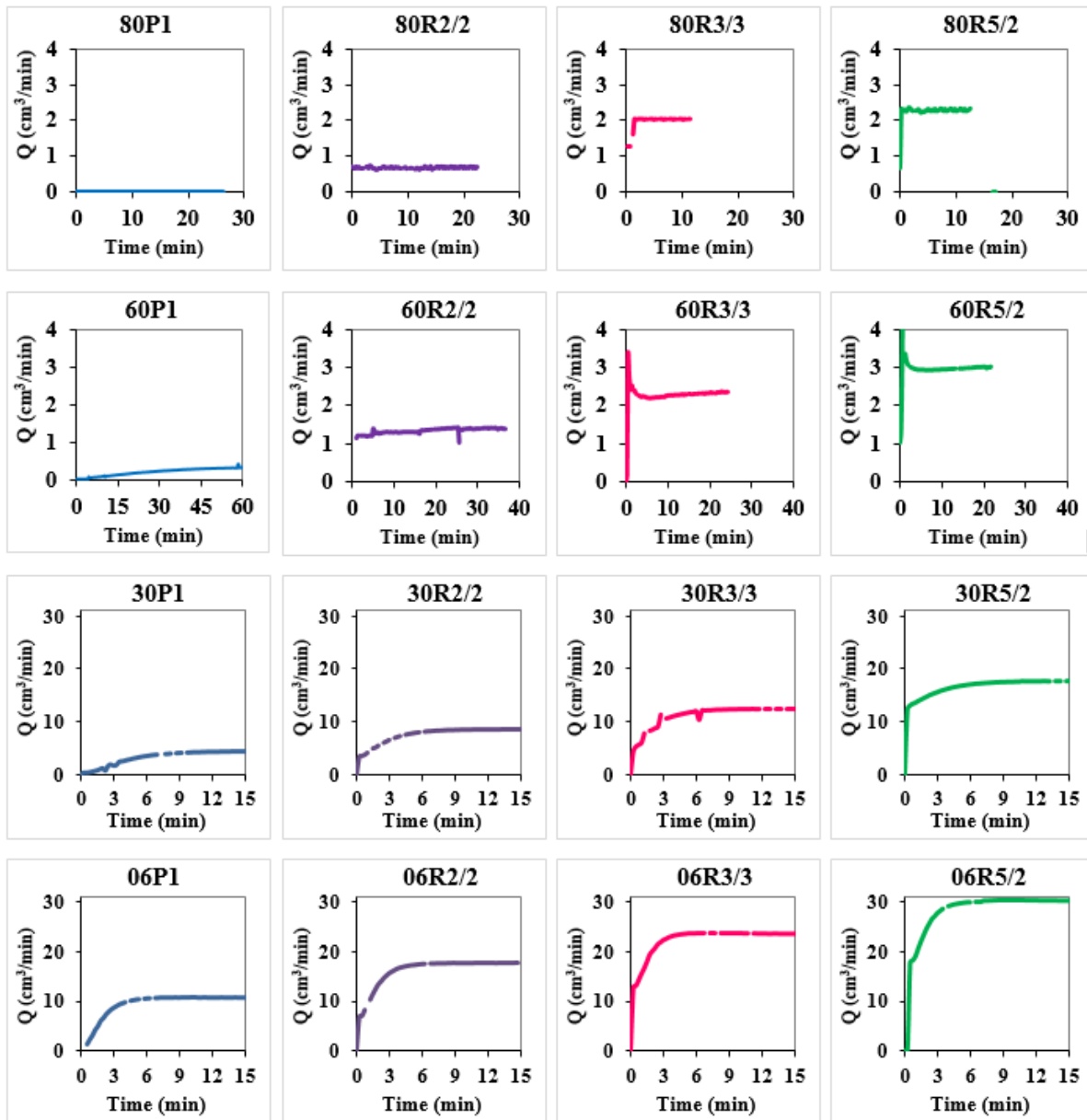
350 **5.3.1. Air flow, Time to Reach Steady State (TRSS) and different permeability zones**

351 The analysis of the kinetics of air flow is necessary to identify and quantify the impact of the
352 presence of reinforcement on gas transfer. Fig. 8 shows the flow kinetics according to the degree of
353 saturation $S_r = 80\%$, 60% , 30% and 6% for one sample of each type (SrP1, SrR2/2, SrR3/3 and
354 SrR5/2). The absolute pressure of the test was 2 bars. At $S_r = 80\%$, no flow was measured through
355 the reference samples, as illustrated by 80P1 in Fig. 8, while flows appeared through all the
356 reinforced samples for this same saturation degree. For reinforced samples, the flow was almost
357 immediate and constant. The flow rates observed through reinforced samples were due to high-
358 permeability zones since plain concrete is not permeable at this saturation degree ($S_r = 80\%$). This
359 zone is called a "defect" in the following.

360 It is very interesting to observe that the flow through reinforced samples reached steady state almost
361 instantaneously after application of the inlet pressure: the TRSS was less than 1 minute. This short
362 time is representative of a medium with very low resistance to the flow (for example, concrete with
363 serious damage, because the defects oppose little resistance to transfer). The poor adhesion between
364 the concrete and the steel bar, and cracks in the concrete near the steel bar led to very low resistance
365 to gas transfer and a flow rate proportional to the defect. If the adhesion was perfect, flow rates of
366 all reinforced concrete would be zero. The presence of this defect can also be expected to modify
367 the concrete transfer properties around the reinforcement during drying. The concrete located in the
368 vicinity of the defect is preferentially drained by its connection to the defect.

369
370 At $S_r = 60\%$, very low air flow was measured in the reference samples (Fig. 8). The flow was smaller
371 than any of the flows through reinforced samples. Initial abrupt increases in the flow were observed
372 for all the reinforced samples (R2, R3 and R5). The jumps were observed 15 seconds after the start
373 of measurement while the flow through the plain concrete was zero. Unlike the previous state ($S_r =$
374 80%), the steady state took longer to become established in reinforced samples at $S_r = 60\%$. The
375 times to reach steady state of reinforced samples increased from 1 minute to 40 minutes when S_r
376 changed from 80% to 60% . At $S_r = 80\%$, the TRSS was very small because it was due to transfer
377 in the defect only (which is very fast) since transfer in concrete was still zero. But at $S_r = 60\%$, the
378 TRSS was relatively long for the plain sample (more than 40 min), because the connectivity of the
379 concrete percolating network was reduced by the presence of water and its tortuosity was increased.
380 Local pressure variations can be more difficult to clear out and impact TRSS. In reinforced samples,
381 the contribution of the concrete could be measured after the initial jump [8] and the TRSS increased

382 due to the slow transfer in concrete as in the plain sample. Nevertheless, it was still the defect that
 383 mainly controlled the gas transfer into the material at $Sr = 60\%$.



384
 385 **Fig. 8:** Air flow kinetics and Time to Reach the Steady State at $Sr = 80\%$, 60% , 30% and 6%

386
 387 At $Sr = 30\%$ and 6% , the pores of the concrete were almost free of water, the air molecules thus
 388 encountered less resistance to their movement in the concrete pores and the TRSS decreased
 389 compared to the state $Sr = 60\%$. However, although the TRSS of the reinforced samples for Sr
 390 lower than 30% were lower than the TRSS for $Sr = 60\%$, they remained higher than the TRSS for
 391 $Sr > 80\%$. In this case, water was not the only factor responsible for the resistance to flow in pores;
 392 pore tortuosity and connectivity also had a greater impact.

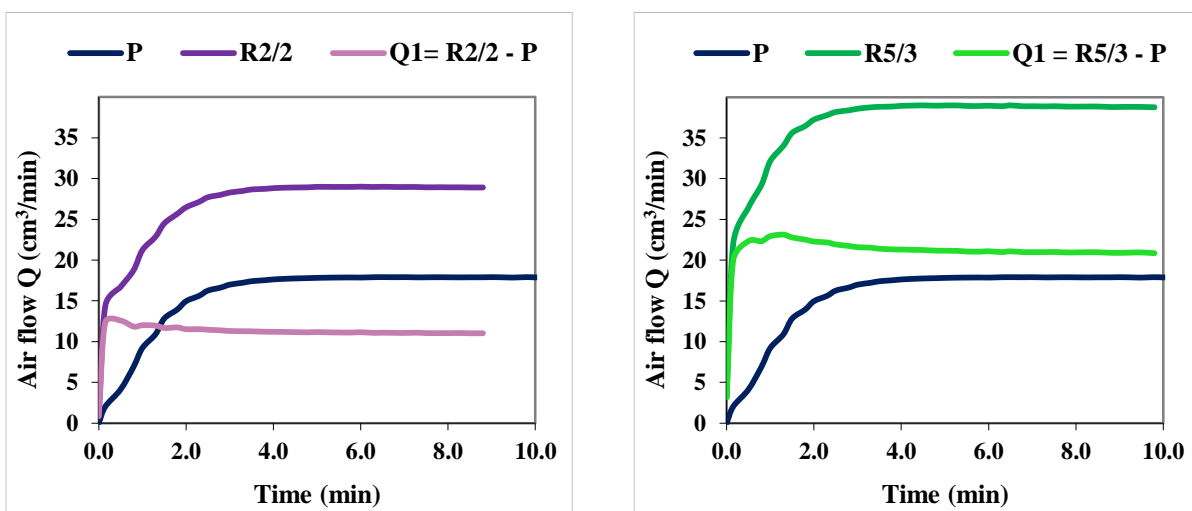
393 The variation of the air flow rate with the saturation degree for the reference sample P (in blue) was
 394 as usual for such measurements [34]. For reinforced samples, the concrete contribution was apparent
 395 after the first jump. Concerning the first jump, the longer the interface was (from R2 to R5), the
 396 greater was the jump. This was verified for all degrees of saturation, thus confirming the importance
 397 of the steel/concrete interface for air flow in reinforced concrete. Permeability tests performed on
 398 concrete thicknesses less than twice the maximum size of the aggregate could be impacted by the
 399 contribution of the interfacial transition zone (ITZ – aggregates-mortar interfaces) to transfer. The
 400 20 or 30 mm of concrete under the reinforcement (R2 and R3 samples) did not create the same
 401 resistance to transfer as in the case of plain samples; it participated in the flow associated with the
 402 defect. The residual thickness of concrete under the reinforcement did not provide a representative
 403 volume in terms of permeability measurement. The consequence could be a preferential path linking
 404 steel/concrete interfaces and interfacial transition zones of aggregate in the concrete under the
 405 reinforcement, which would amplify the impact of the defect. However, this thickness was of the
 406 same order as that of the concrete cover in many real structures.

407

408 5.3.2. Concrete contribution to air flow kinetics

409 To analyse the contribution of concrete to the air flow through reinforced samples, the air flow
 410 corresponding to the contribution of the interface and cracks (referenced Q_1) was subtracted from
 411 the curve. In order to determine the flow Q_1 , the plain concrete curves were first subtracted from the
 412 reinforced concrete curves. As shown in Fig. 9, the result of the subtraction, Q_1 , was quite constant
 413 after 30 seconds of measurement.

414



(a)

(b)

Fig. 9: Air flow $Q(t)$ – calculation of Q_1 ($S_r = 0\%$)

415

416 Constant flows Q_1 were subtracted from the curves of reinforced samples for the samples at
417 saturation degrees lying between 0 and 30% (Fig. 10). For the high saturation degrees (60% and
418 80%), the contribution of the plain concrete was low or negligible and the representation was not
419 useful.

420

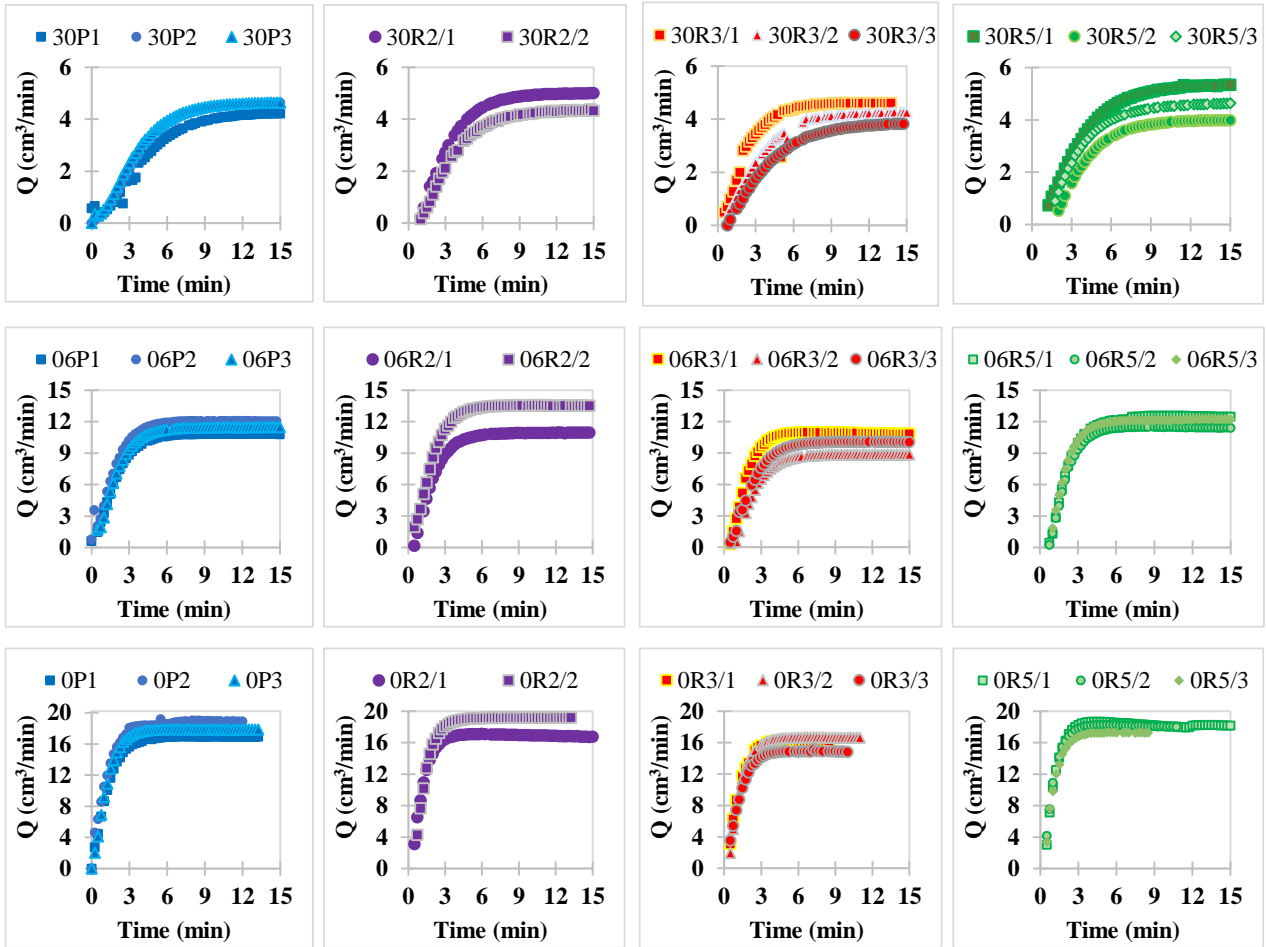


Fig. 10: Correction of curves for all samples for $S_r = 0\%$, 6% and 30%

421 After the subtraction of the initial jump, all the air flows had the same kinetics (Fig. 10). The
422 corrected curves are representative of the contribution of the sound concrete to transfer whatever
423 the depth of reinforcement. This confirms that the beginning of the curve of air flow $Q(t)$ is highly
424 representative of the defect due to the interface and induced cracks. The slight differences observed
425 in flow kinetics after subtraction (Fig. 10) may be due to the heterogeneity of the samples, which
426 can be high since cracks are involved in air flow through reinforced samples.

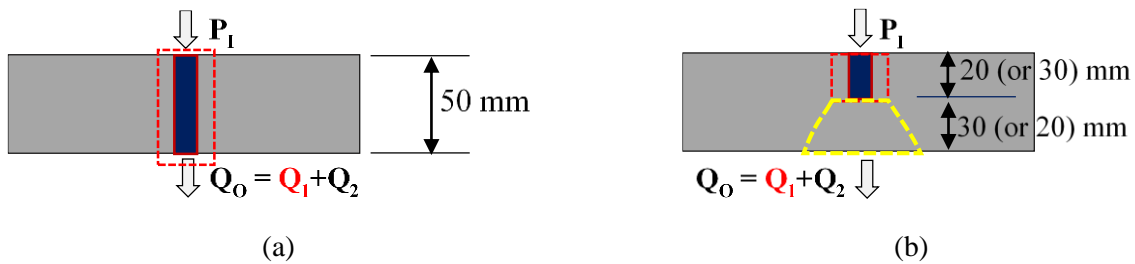
427 In presence of reinforcement, two mechanisms act on transfer in concrete: the air flow in the
 428 interface and induced cracks, and the usual air flow in sound concrete. The transfer in the plain
 429 concrete does not appear to be greatly affected. Modelling has to consider the two phenomena in
 430 order to be representative of concrete in real structures.

431

432 5.4. Discussion

433 The different permeability zones in reinforced concrete are schematized in Fig. 11. In the case of
 434 R5, the interface crosses the whole sample and links the two sample faces. It can provide a transfer
 435 pathway according to the nature of the steel/concrete interface (Fig. 11-a). For R2 and R3, the
 436 interface does not link the two faces directly (Fig. 11-b) but the previous analysis has pointed out
 437 that it can also lead to a preferential pathway between the two faces since abrupt increases in air
 438 flow were observed in all reinforced R2 and R3 samples (Fig. 8).

439



Legend. Q_0 = Total air flow; Q_2 = flow through concrete only; Q_1 = flow through the defect

440

Fig. 11: Permeability zones in R5 (a) and permeability zones in R2 and R3 (b)

441 The variation of the effect of reinforcement according to the degree of saturation can be quantified
 442 in terms of permeability (Fig. 7), in terms of relative air flows compared to the total flow Q_0 (Fig.
 443 12) or in terms of equivalent crack opening (Fig. 14). The definition of the relative air flows in Fig.
 444 12 is:

- 445 - Q_1/Q_0 , ratio between the flow due to the presence of the interface and the total air flow into
 446 the sample,
- 447 - Q_2/Q_0 , ratio between the flow through the concrete and the total air flow into the sample
 448 (Fig. 12).

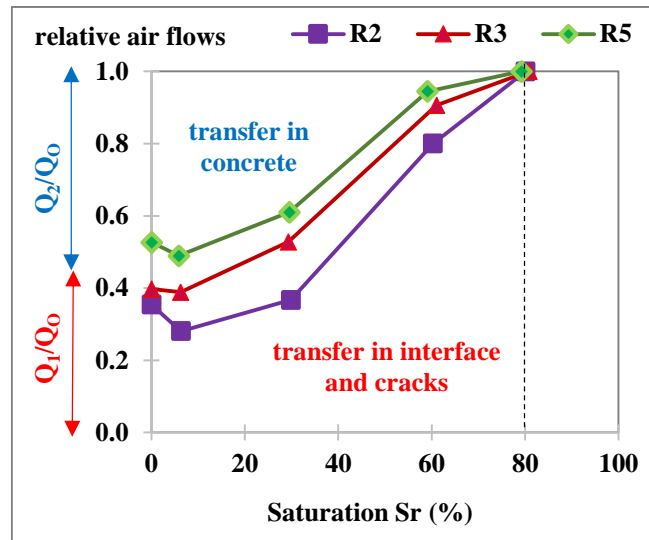


Fig. 12: Relative air flows in reinforced samples according to saturation degree

449 In terms of relative permeability, the impact of reinforcement was the greatest for degrees of
 450 saturation lying between 60 and 80% (Fig. 7-b). The comparison of the flows Q_1 and Q_2 confirms
 451 this result (Fig. 12): the contribution of the defect to transfer is all the more important when the
 452 saturation level is high.

453 These observations can be analysed in three points:

- 454 - For saturated samples (Sr equal to 100%), the whole concrete porosity and steel-concrete
 455 interfaces are filled by water and samples are totally impermeable to gas,
- 456 - At high degrees of saturation (Sr equal to 60% and 80% in the experiments), the permeability
 457 of plain concrete is still zero (Fig. 7), which is not the case for reinforced samples. This means
 458 that steel-concrete adherence is not perfect and impacts gas transfer because of its direct
 459 connection with the surface in the case of R5. In the case of the samples R2 and R3, it indicates
 460 that there is not only the pathway created by steel-concrete interfaces but also a continuity of
 461 the defect in the concrete below the steel (Fig. 11-b), which can be induced by the presence
 462 of cracks and by pathways through interfacial transition zones of aggregates. In high states of
 463 saturation, the steel-concrete interfaces and induced cracks are thus the main transfer vector
 464 in reinforced samples (Fig. 12). This result has an implication for the durability of structures:
 465 the concrete in situ is generally subjected to high levels of water saturation [43], and the
 466 percentage of transfer through concrete skin by cracks could be particularly high compared to
 467 transfer through concrete (Fig. 12). It could be the main mechanism to be considered for
 468 transfer through the concrete skins of structures.

469 - At low degrees of saturation, the pores of the concrete surrounding the reinforcement are
470 gradually emptied of water, which increases the contribution of concrete to the air flow (Fig.
471 12). Moreover, the impact of concrete shrinkage on transfer is amplified. The shrinkage
472 induced by drying is restrained by the rigid inclusion of the steel bar in the reinforced samples,
473 where it leads to tensile stresses in the concrete and to cracks. Consequently the pores can be
474 connected to the cracks and to the steel-concrete interface, the consequence being an increase
475 in gas transfer. These cracks were already present in reinforced samples for saturation degrees
476 between 60% and 80%. At low saturation degrees, shrinkage strains are greater and the
477 induced cracks grow, thus possibly increasing the contribution of the defect to the air flow.
478 However, the relative contribution of a defect decreases with decreasing degree of saturation
479 (Fig. 12): for a low saturation state, the proportion of transfer in the concrete increases faster
480 than the contribution of the defect, except for a saturation degree equal to 0, for which the
481 contribution of the defect increases suddenly, probably because the high drying temperature
482 (105°C) between 6 and 0% leads to associated damage.

483 These phenomena contributed to the greater relative permeability of reinforced samples (Fig. 7).
484 In order to complete this analysis, samples were observed with a video microscope (Keyence VH-
485 5911, maximum magnification x 175). Fig. 13 shows a microscopic view of the steel-concrete
486 interface of the sample R5/1 (magnifications x 25 for Fig. 13-a and x 175 for b).

487

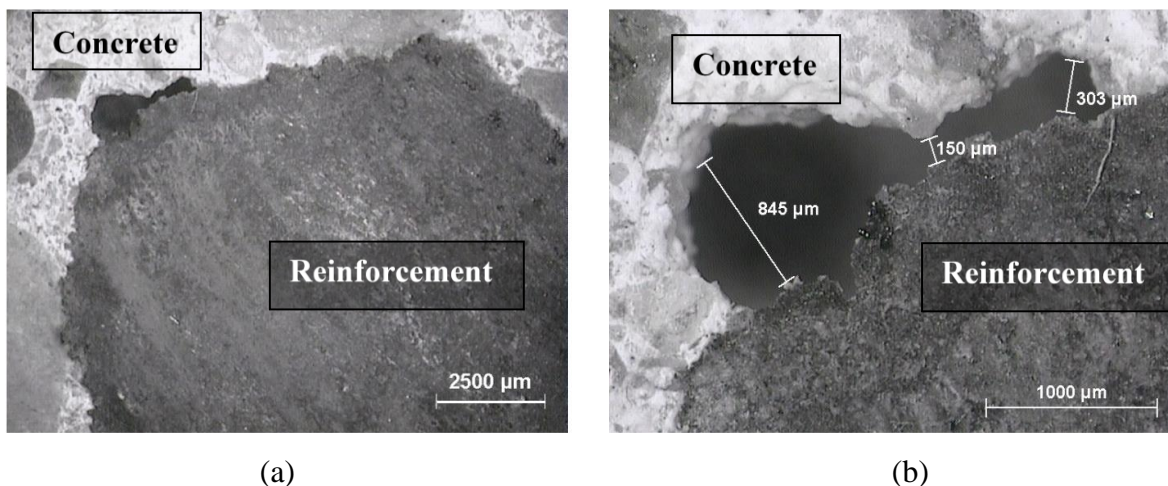


Fig. 13: Detachment of the reinforcement from the concrete at steel-concrete interface

488 As could be expected, the geometry of the interface was very complex. The microscopic observation
489 indicated the presence of some irregular voids in the contact between concrete and steel. The voids
490 did not cross the sample but were localized (Fig. 13-b) as already observed by Mohammed and al.
491 [44]. With the precision of the apparatus used here, no detachment appeared anywhere around the

492 reinforcement (Fig. 13-a). However, detachments with openings smaller than 10 μm may exist.
493 They would not be observable with this video microscope. The specimens would have to be sawn
494 for more precise apparatus to be used. This was not done since it could lead to the interface being
495 modified.

496 To quantify the opening necessary to obtain the measured permeability, equivalent crack openings
497 were calculated from flows. For this purpose, the defect caused by the interface and the induced
498 cracking was modelled as a single perfect crack with an equivalent crack opening, w , completely
499 surrounding the steel bar. This opening was determined from the air flow Q_1 , which characterizes
500 the impact of the defect on the permeability. Different works propose a determination of the crack
501 opening w from air flow [15], [17], [45]. The equation below (2) is drawn from Mivelaz's work [16]:

$$w^3 = \frac{24 \mu L R T Q_1}{\xi (P_I^2 - P_O^2)} \quad (\text{Eq. 2})$$

502 where μ is the dynamic viscosity of the fluid at the test temperature (Pa.s), P_I the inlet pressure
503 (absolute) (Pa), P_O the outlet pressure - assumed to be equal to the atmospheric pressure (Pa)
504 in this test, R the gas constant (J/kg/K), T the temperature (K) and ξ a flow coefficient that
505 essentially characterizes the network tortuosity.

506 During the test, the evolution of the flow is characteristic of the presence of different defects. To
507 quantify the impact of these defects on permeability, the tortuosity, the connectivity, the
508 constrictivity of the pore network, and the interactions between cracks and concrete porosity should
509 be taken into account. The importance of each parameter for permeability depends on the geometry
510 of the actual percolation path which is difficult to characterize. However, the measured flow
511 highlights the range of the impact and allows a simplified evaluation. This calculation assumes
512 constant thickness for the defect. In order to quantify the approximation of this approach, the
513 calculation is performed for two extreme values of the flow coefficient ξ . Thus, the impact of the
514 geometry of the percolation path on permeability is evaluated.

515 This approach was chosen because it took only a few parameters (w and ξ) into account in
516 comparison with others. According to Ripphaussen [46], cited by Mivelaz [16], the flow coefficient,
517 ξ , is defined as the ratio of flow through cracks with an opening of w and the theoretical flow through
518 two smooth parallel planes having the same opening, w . ξ is then less than 1 and takes the roughness
519 and the tortuosity of the transfer path into account. The equivalent crack of width w is assumed to
520 be all around the reinforcement over the entire sample thickness. Its length is equal to the thickness
521 of the samples (L). The flow coefficient, ξ , is assumed to be constant while, in reality, the crack
522 network is modified by drying and the coefficient could increase for the lowest saturation degree.
523 The calculated opening is approximate and does not represent reality but it enables the impact of

524 the opening due to steel-concrete interfaces on the concrete permeability to be analysed and
 525 compared. The defect openings thus calculated are presented in Fig. 14 for a relative inlet pressure
 526 of 1 bar and for two extreme assumptions of flow coefficient, ξ :

- 527 - A flow coefficient, ξ , of 1, which represents direct transfer [16],
- 528 - A flow coefficient, ξ , of 0.08, which represents usual transfer in a diffusive cracking pattern
 529 in concrete [16], [47].

530 The mean values and standard deviations presented in Fig. 14 were obtained from the values for all
 531 samples tested (except SrR2/3 as explained above).

532

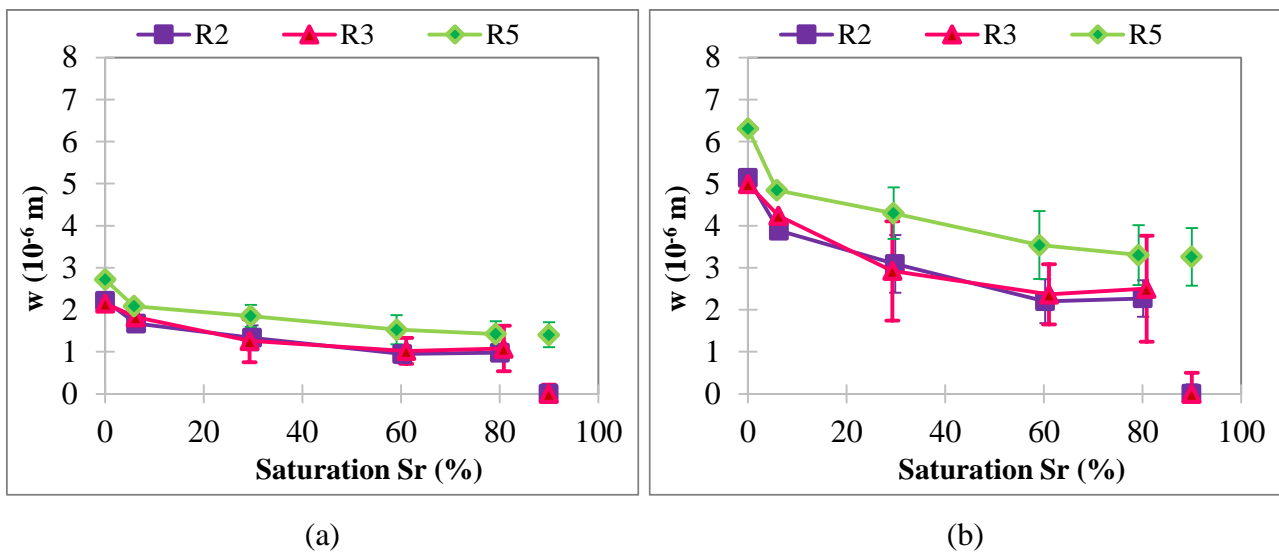


Fig. 14: Defect opening, w , for two assumptions of flow coefficient, ξ , equal to 1 (a) and 0.08 (b)

533

534 Between 0 and 80% of saturation, two slopes can be distinguished in the variation of the defect
 535 opening w :

- 536 - A fairly constant evolution between $Sr = 80\%$ and 6%
- 537 - A marked change of gradient for the last drying between $Sr = 6\%$ and 0% .

538 This change for the lowest saturation degree could be due to notable damage occurring in the
 539 concrete during the drying at $105\text{ }^{\circ}\text{C}$. The increase of the calculated opening w presented in Fig. 14
 540 globally quantifies the increase of transfer properties of the defect with drying. In reality, it may be
 541 partially due to the increase of the opening but it is probably also due to the movement of water out
 542 of the cracks and to the increase in crack connectivity, all of which all make transfer easier in the
 543 samples.

544 All the calculated values of opening w are close and lie below $7\text{ }\mu\text{m}$ whatever the assumptions on
 545 the flow coefficient, ξ (Fig. 14). Unlike the localized voids observed under the microscope (Fig. 13),

546 which did not cross the samples, the calculated detachments had to cross the samples to obtain the
547 flows measured during permeability tests. No measurement was performed between 100% and 80%
548 with the same preconditioning of samples. As defects with openings greater than 1 μm are drained
549 at very high relative humidity (up to 99%, Kelvin Laplace equation), the air transfer in interfaces
550 (and in cracks) could be expected to be between 80% and 99% for such openings. In reality, it
551 depends on the morphology of the pathways. If there are only pathways with large openings (greater
552 than 1 μm), a sample should be permeable even at very high degrees of saturation (higher than 95%)
553 but, if the defect is composed of several pathways with smaller openings (less than 1 μm), it can
554 become airtight for lower degrees of saturation. Consequently, to complete the evaluation of the
555 pathways in the different samples, another degree of saturation was studied. For this purpose,
556 samples were initially saturated with water under vacuum and then stored in an air-controlled test
557 room (RH of 60% and temperature of 20°C) for only one day. The objective of this additional
558 preconditioning was to drain only the defects, such as the steel/concrete interface, but to keep the
559 percolating network of the concrete full of water. In these conditions, the concrete sample was still
560 wet even if its surface was slightly dry. The global saturation rate of these samples is about 90%
561 after this preconditioning. The permeability test was then performed and showed that:

- 562 - the air flow through plain samples was still zero,
- 563 - the air flows through reinforced samples R2 and R3 were zero, and the equivalent opening
564 w was thus zero for this saturation degree (Fig. 14),
- 565 - the air flow through reinforced concrete R5 was not zero and the equivalent crack opening
566 calculated was equal to the opening obtained for 80% (Fig. 14).

567 Results on R2 and R3 indicate that the defects that crossed the samples at 80% no longer formed a
568 pathway for air flow at larger saturation degrees: the concrete below the steel bar (thickness: 20 mm
569 for R3 and 30 mm for R2) was not permeable to gas at 90% saturation and so resisted gas transfer
570 into the material. Results on R5 show that, apart from localized voids, there was actually a connected
571 interface between the steel bar and the concrete, which crossed the entire thickness of the samples.
572 Its equivalent opening was effectively smaller than 5 μm and could not be seen in the microscopic
573 analysis (Fig. 13).

574 The impact of reinforcement bars on permeability studied in this work should be dependent on
575 numerous parameters (concrete composition, steel bars diameter, confinement pressure...).
576 Concerning concrete composition, aggregate size and composition should impact the effect as it
577 modifies the ITZ porosity [48]–[50]. Decreasing the aggregate size could lead to increase the
578 tortuosity in the percolation paths due to ITZ and thus to decrease the connection between the
579 external environment and steel bars. The impact of steel bars on permeability could be lower for

580 concrete with smaller aggregate. The impact of steel bar diameters would be dependent on steel /
581 concrete ratio. For a same volume of concrete, the volume of voids at the interface should be lower
582 for bars with smaller diameter. It should lead to smaller modification of permeability. At the
583 opposite, for a same steel / concrete ratio, using smaller bars would lead to increase the number of
584 bars. Each bar should create percolation paths. It should lead to increase the global permeability.
585 Future works should quantify precisely this effect. The confinement pressure applied to the
586 specimen can also modify the results. In this program, six pressures lying between 3 and 9 bars were
587 used for R5 sample (reinforcement crossing the sample) at the lowest saturation degree. As
588 expected, no modification of the permeability was noted for plain samples. Such confinement
589 pressures are too low to imply the reduction of the porosity. For reinforced samples, a decrease of
590 the flow were observed for increasing pressure as the pressure leads to the closure of the interface
591 (decrease of 6% of the permeability for pressure increasing from 3 to 9 bars). In case of damaged
592 concrete, the application of confining pressure can decrease the opening of the existing cracks but
593 the relative displacements of cracks lips prevent total reclosure. Decrease of flow can be expected
594 as long as the confinement pressure does not lead to supplementary cracking.

595 The results presented in this paper cannot be directly extended to water permeability. Indeed,
596 movements of water in such interfaces would lead to the combination with numerous chemical
597 mechanisms: additional hydration of cement, precipitation of new phases, and steel corrosion
598 according to water composition and pressure [51]. The objective of the study was to decrease such
599 risk of interaction and future works should analyse the impact of combination between potential
600 cicatrisation in case of water transfer.

601 The high flow rate observed through the defects and the increase in permeability with reinforcement
602 emphasized the great connectivity of the pores and steel/concrete interfaces in the reinforced
603 samples. In literature, Singh and Singhal showed the decrease of permeability with the inclusion of
604 steel fibres in concrete for unloaded concrete [21]. For fibres reinforced concrete, the percolation
605 path induced by the steel fibres is discontinuous and the cracks which could be induced by restrained
606 shrinkage would be smaller than in plain concrete. Such small cracks would have little impact on
607 permeability [19], [20]. At the opposite, the presence of usual steel reinforcement in concrete
608 induces continuous and larger percolations paths. Such continuous paths can largely impact
609 permeability as shown in the present study. In conclusion, small continuous defects in concrete,
610 such as steel/concrete interfaces and small concrete skin cracks can lead to permeability twice that
611 expected for the plain samples usually used for permeability measurements. This illustrates and
612 quantifies the risk associated with the use of measurements on plain concrete to evaluate and predict
613 the transfer behaviour of real structures. Modelling based on permeability obtained on plain samples

614 should take the impact of cracks and interfaces into account to obtain more relevant calculations,
615 particularly close to the concrete skin. The experimental programme presented in this paper can thus
616 be used to evaluate the scatter on concrete permeability due to the presence of reinforcement.

617 **6. Summary**

618 Permeability characterizes the ability of materials to resist the penetration of aggressive agents. It is
619 an important indicator of durability for structures in reinforced concrete. The presence of
620 reinforcement affects the concrete cover and the permeability. The present study contributes the
621 following results:

622
623 (a) The presence of steel bars embedded in concrete, in parallel with the flow associated with the
624 inlet pressure, leads to an increase of the permeability of the composite material due to the steel-
625 concrete interface (particularly porous) and to cracking induced by restrained shrinkage (which can
626 be connected with the steel-concrete interface). In these interfaces and induced cracks, the transfer
627 is accelerated,

628
629 (b) Steel-concrete interfaces modify the gas flow kinetics in reinforced concrete. For reinforced
630 samples, tests showed that two transfer mechanisms existed: a sudden jump reflecting the effect of
631 the steel-concrete interface and a more progressive transfer, characteristic of the permeability in
632 concrete,

633
634 (c) At high degrees of saturation (above 60% moisture saturation), the concrete-steel interface is the
635 main gas transfer vector in reinforced concrete; it is desaturated and connected to the surface while
636 the concrete remains impermeable to gas. It is important to model permeability in structures
637 subjected to a variety of environmental conditions.

638
639 (d) By representing the defect as a crack, the equivalent opening can be calculated from the air flow.
640 The evolution of the damage of the steel-concrete interface with drying is reflected by an increase
641 in the opening of the equivalent crack. Even small defects (equivalent opening of some micrometres)
642 are sufficient to obtain permeability twice that measured on plain concrete. This should be taken
643 into account in calculations used for prediction.

644
645 Finally, the present study opens up perspectives for the characterization and quantification of the
646 geometry of the steel-concrete interface according to the type of reinforcement. For this, it will be
647 necessary to continue the experimental programme on different types of steels and different

648 thicknesses of samples. These studies would contribute to better predictions of the durability of
649 reinforced concrete structures.

650

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