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Water transport properties of virtual fractal porous media: implications for the unsaturated transport properties of cement-based materials

4

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15

16 Abstract

17 Cement-based materials are more and more recognized as fractal materials. From a practical 18 point of view, fractality means that the pore size distribution can be described using fractal 19 scaling law (i.e. power functions). Here, the simplest scaling law making use of a single fractal 20 dimension was used to generate simple and virtual fractal porous media (based on bundles of 21 parallel cylindrical pores). The capillary curve and permeability (relative and intrinsic) of the 22 virtual porous media were then estimated through theoretical and numerical approaches. The 23 results show that: (1) although bereft of any physical basis, van Genuchten equation bears some 24 fractal information; (2) although highly flexible, van Genuchten equation fails to perfectly fit the 25 capillary curves and can thus generate error in inverse analysis (for intrinsic permeability 26 evaluation) and (3) there seems to be a relation between the intrinsic permeability and van 27 Genuchten pressure parameter.

28

29 Keywords: Pore Size Distribution; Adsorption; Permeability; Fractal

30

31 **1. Introduction**

Concretes and cement-based materials are ubiquitous in construction because they are versatile
 and affordable. Even though they have been broadly used and studied for decades, they remain

- 34 difficult to apprehend and describe because of their multiphasic, multiscale and porous nature.
- 35 For instance the pore-structure itself spans over several orders of magnitude in dimension -
- 36 from the angstrom (10^{-10} m) up to the micrometer (10^{-6} m) or more and it is still not possible
- 37 today to obtain a clear view of the whole pore-structure even with the use of different
- 38 experimental techniques [1,2]. The main consequence is that some concrete macroscopic
- 39 properties that are strongly dependent on the pore-structure (such as transport properties)
- 40 remain difficult to assess and often have to be tested experimentally.
- 41 It has been however known for years that the pores or at least a fraction of them exhibit
- 42 fractal properties [3–11]. This was proven for the smaller pores (C-S-H pores) using small-angle
- 43 x-ray (SAXS) or neutron scattering (SANS) [3,4,6,12–18]; for the larger pores using image

- 44 analysis (optical and/or electronic microscopy) [6–8,19] and of course using mercury intrusion
- 45 porosimetry (MIP) [20–26]. All these results are far from being consistent as there is a strong
- 46 scatter in the resulting fractal dimension values (they all lie between 1.0 and 3.5). Moreover it
- has also been suggested recently, using MIP results, that the fractality of the pore-structure was
 scale-dependent; the fractal dimension would not be not unique and there would exist at least
- 46 scale-dependent, the fractal dimension would not be not diffue and there would exist at least 49 two dimension domains each having a different value of the fractal dimension [20–23,25,27].
- 50 The reader should keep in mind that MIP is a flawed technique that misallocates pore size and
- 51 can generate damage [28–32] (and then misestimate fractal dimensions); all the evaluations
- 52 obtained using MIP then only should be taken with great caution. However, the scale
- 53 dependence of the MIP fractal dimensions is consistent with the scatter obtained with the other
- 54 techniques. In the author's mind, the cementitious materials are more than likely to be
- multifractal materials although the corresponding scale domains and fractal dimensions remain
 uncertain.
- 57 Pore fractality is an important feature because it means that the pore structure is similar at
- 58 different scales. From a mathematical point of view, this implies that the pore size distribution
- should follow a simple scaling law in the form of r^{-D} where r is the pore radius and D the fractal
- 60 dimension (a constant) [33]. The pore-size distribution can then be described using with simple
- 61 power functions. It is the objective of this article to take advantage of using these simple
- 62 analytical equations that describe fractal pore-size distribution in order to generate virtual
- 63 porous media to be used as model materials to study the water transport properties of
- 64 unsaturated concretes.

70

66 **2. Unsaturated transport properties**

In low permeable unsaturated concretes, it was shown that water transport was mainly due tothe permeation of liquid water [34]. It is then possible to describe unsaturated water transport

69 using a single equation [35,36]:

$$\phi\left(\frac{\partial S}{\partial P}\right)\frac{\partial P}{\partial t} = div\left[\left(\frac{Kk_r}{n}\right)\underline{grad}(P)\right]$$
(1)

71 where \emptyset is the porosity; *S* the saturation index; *P* pressure of liquid water in the pores (Pa); *K*

intrinsic permeability (m²); k_r relative permeability to water and η water viscosity (Pa s).

It is common practice to use the equation proposed by van Genuchten [37] to fit the capillarycurve (relationship between pressure *P* and saturation *S*):

75
$$\begin{cases} S(P) = \left[1 + \left(\frac{P}{P_0}\right)^{\frac{1}{1-m}}\right]^{-m} \\ P(S) = P_0 \left(S^{-\frac{1}{m}} - 1\right)^{1-m} \end{cases}$$
(2)

where m and P_0 are two positive constant, P_0 is equivalent to a pressure (in Pa). The left-hand term of equation (1) then writes:

78
$$\phi\left(\frac{\partial S}{\partial P}\right) = -\frac{m\phi}{(m-1)P_0} \left(\frac{P}{P_0}\right)^{\frac{m}{1-m}} \left[1 + \left(\frac{P}{P_0}\right)^{\frac{1}{1-m}}\right]^{-1-m}$$
(3)

79 The relative permeability k_r is almost never characterized through experiments; rather it is

commonly evaluated using the model proposed by Mualem [38] that uses the capillary curve asinput data:

82
$$k_r = \sqrt{S} \left[\frac{\int_0^S \frac{du}{P(u)}}{\int_0^1 \frac{du}{P(u)}} \right]^2$$
(4)

- 83 When van Genuchten equation [37] is used together with the model of Mualem [38], the well-
- 84 known following simple analytical expression aka known as Mualem-van Genuchten (MVG) is
- 85 obtained:

$$\begin{cases} k_r(S) = \sqrt{S} \left[1 - \left(1 - S^{\frac{1}{m}} \right)^m \right]^2 \\ k_r(P) = \left[1 + \left(\frac{P}{P_0} \right)^{\frac{1}{1-m}} \right]^{-\frac{m}{2}} \left(1 - \left(\frac{P}{P_0} \right)^{\frac{1}{1-m}} \left[1 + \left(\frac{P}{P_0} \right)^{\frac{1}{1-m}} \right]^{-m} \right)^2 \end{cases}$$
(5)

87 Finally, it must be recalled that the value of the intrinsic permeability *K* is preferably assessed

- 88 through inverse analysis as those measured using water or gas are known to overestimate
- 89 flowrates [39].
- 90

91 **3. Definition of a fractal porous medium (FPM)**

92 3.1. Pore-size distribution, porosity

Here, the cementitious materials were considered as ordinary fractal materials, i.e. with a unique

94 fractal dimension. This choice clearly goes against what is commonly observed (i.e. different

95 fractal dimensions over different size ranges). This choice was made to favor the simplicity of

96 the approach in order to test and illustrate ideas, but this was done to the detriment of

97 representativeness... Let us consider a relative elementary volume (REV) of a virtual fractal

porous material in which the pores are constituted of straight, independent and parallel open-

ended cylinders of radius between R_m and R_M (with $R_M \gg R_m$). The REV is a cube of dimension

100 L_0 in which the cumulated number of pores follows a fractal scaling [33,40–42]:

101
$$\forall r \in [R_m; R_M] \ N(\rho \ge r) = \left(\frac{r}{R_M}\right)^{-D}$$
(6)

102 where *N* is the cumulated number of pores of radius greater than *r* and *D* the fractal dimension 103 (with 1 < D < 2).

104 It is noticeable that, by definition, there is only one pore of radius *R*_M. Increasing the value of the

- 105 fractal dimension obviously increases the total number of pores but also the relative
- 106 contribution of the smallest pores (Figure 1).
- 107





- 110
- 111 The number of pores of radius *r* is easily obtained by differentiation of eq. (1):

112
$$n(r) = |dN| = DR_M^D r^{-D-1} dr$$
(7)

113 The total porosity \emptyset of such a fractal porous medium is then:

115 Expectedly, the value of the porosity depends on the pore-size interval $[R_m; R_M]$, fractal

dimension D and also on the dimension of the REV L_0 . The evaluation of the latter is not 116

straightforward; in other words there is no evident exact method to evaluate L_0 . Alternatively, an 117

estimate can be obtained by considering that the porosity value (ϕ_0) is known (it usually lies 118

119 between 30 and 40% for hardened cement pastes), the REV dimension L_{θ} of a fractal hcp can

120 then be estimated following:

121
$$\phi_0 = \frac{\pi D R_M^D}{(2-D)L_0^2} (R_M^{2-D} - R_m^{2-D}) \Rightarrow L_0 = \sqrt{\frac{\pi D R_M^D}{(2-D)\phi_0}} (R_M^{2-D} - R_m^{2-D})$$
(9)

Using $\phi_0 = 35\%$; $R_m = 3 \times 10^{-10}$ m; $R_M = 1 \times 10^{-6}$ m and D = 1.5 as input data, equation (4) yields $L_0 \approx 5 \times R_M$ and then $L_0 \propto R_M$. 122 123

124

125 3.2. Water retention

126 The water retention curve of the FPM was evaluated using a simple approach that considers that 127 water is retained due to (i) physical adsorption of water molecules on the pore walls and (ii) capillary condensation [43-46] (more details in [47]). Adsorption was assumed to result in a 128 129 unique water layer (monolayer), the thickness of which (t_w) was described using Langmuir's 130 model [48]:

 $t_w(h) = \frac{kt_m h}{1+kh}$ 131 (10)

where *h* is the relative humidity (without unit); *k* Langmuir's equilibrium constant (without 132

unit) and t_m the thickness of the complete monolayer (m). The value of these two parameters 133

was set to k = 50 and $t_m = 3 \times 10^{-10}$ m (3 Å) following Morgan & Warren [49], Harkins & Jura [50], Hagymassy [51] and Yamanaka [52]. The pore saturation induced by adsorption is then: 134

135

136
$$S_a(h) = \frac{1}{\emptyset L_0^3} \int_{R_m}^{R_M} (2\pi r L_0) t_w(h) n(r) = 2t_w(h) \left(\frac{2-D}{1-D}\right) \left(\frac{R_M^{-D} - R_m^{1-D}}{R_M^{2-D} - R_m^{2-D}}\right)$$
(11)

137 Capillary condensation was described using the well-known Kelvin equation that determines the 138 maximal value of the pores radius r_K in which condensation occurs:

139
$$r_K(h) = -\frac{2M\sigma}{\rho RT \ln(h)}$$
(12)

140 where *M* is the water molar mass (18×10⁻³ kg/mol); σ surface tension (0.072 N/m); ρ water

141 density (998.3 kg/m³ at 20°C); R ideal gas constant (8.3145 J/mol/K); T absolute temperature

142 (273.15 K) and *h* relative humidity (without unit).

143 The reader must keep in mind that the presence of the adsorbed film reduces the apparent

radius of the pores and thus condensation occurs in pores of radius lower than $(r_K + t_w)$ instead 144 145 of r_K . The pore saturation induced by capillary condensation is then:

146

$$S_{c}(h) = \frac{1}{\emptyset L_{0}^{3}} \int_{R_{m}}^{r_{K}+t_{w}} (\pi r^{2} L_{0}) n(r) - \frac{1}{\emptyset L_{0}^{3}} \int_{R_{m}}^{r_{K}+t_{w}} (2\pi r L_{0}) n(r) t_{w}(h)$$

$$= \left[\frac{(r_{K}+t_{w})^{2-D} - R_{m}^{2-D}}{R_{M}^{2-D} - R_{m}^{2-D}} \right] - 2t_{w}(h) \left(\frac{2-D}{1-D} \right) \left[\frac{(r_{K}+t_{w})^{1-D} - R_{m}^{1-D}}{R_{M}^{2-D} - R_{m}^{2-D}} \right]$$
(13)

147 Eventually, the saturation is the sum of the two contributions (adsorption and condensation):

148
$$S(h) = S_{c}(h) + S_{a}(h) = \left[\frac{(r_{K}+t_{w})^{2-D} - R_{m}^{2-D}}{R_{M}^{2-D} - R_{m}^{2-D}}\right] + 2t_{w}(h)\left(\frac{2-D}{1-D}\right)\left[\frac{R_{M}^{1-D} - (r_{K}+t_{w})^{1-D}}{R_{M}^{2-D} - R_{m}^{2-D}}\right]$$
(14)

149 The saturation proves to be a simple analytical function, with only two terms that depend on the

150 pore-size interval $[R_m; R_M]$ and fractal dimension *D*. it is noteworthy that when $(r_K + t_w)(h) =$

 R_M all the pores are filled with water and then S = 1. Otherwise, when $(r_K + t_w)(h) = R_m$ there 151 is no condensed water but the saturation is not nil because of the presence of the adsorbed film 152

 $(1)(2-D)(R_{M}^{1-D}-R_{m}^{1-D})$ 0.

153 on the pore walls and so
$$S = 2t_w(h) \left(\frac{2-b}{1-b}\right) \left(\frac{m_M}{R_M^{2-D}-R_m^{2-D}}\right) > 0$$

154

3.3. Intrinsic permeability 155

156 To compute the permeability of the FPM, one must start with Poiseuille law that gives the flow 157 through a cylinder of radius r and length L_0 :

158
$$q(r) = \frac{\pi r^4}{8\eta} \left(\frac{\Delta P}{L_0}\right)$$
(15)

159 where μ is the dynamic viscosity of water (1.0016×10⁻³ Pa s at 20 °C) and ΔP the pressure

160 difference between the inlet and outlet of the cylinder.

161 The flow through all the pores of the fractal porous medium is then the sum of the contributions 162 of all the pores:

163
$$Q_t(r) = \int_{R_m}^{R_M} \left[\frac{\pi r^4}{8\eta} \left(\frac{\Delta P}{L_0} \right) \right] n(r) = \frac{\pi}{8\eta} \left(\frac{\Delta P}{L_0} \right) DR_M^D \int_{R_m}^{R_M} r^{3-D} dr = \frac{\pi DR_M^D}{8\eta(4-D)} \left(\frac{\Delta P}{L_0} \right) \left(R_M^{4-D} - R_m^{4-D} \right)$$
(16)

164 One can easily calculate the apparent permeability K_e of the fractal porous medium considering 165 that:

166
$$Q_t(r) = \frac{K_e}{\eta} L_0^2 \left(\frac{\Delta P}{L_0}\right) = \frac{\pi D R_M^D}{8\eta(4-D)} \left(\frac{\Delta P}{L_0}\right) (R_M^{4-D} - R_m^{4-D}) \implies K_e = \frac{\pi D R_M^D}{8(4-D)L_0^2} (R_M^{4-D} - R_m^{4-D})$$
(17)

167 It is clear here that the pores were assumed to be straight (without tortuosity); this was done on

purpose to make the model as simple as possible and also because pore-tortuosity is already 168

169 accounted for in Mualem model [38] and there was no use of accounting for it twice. The reader

170 should however be informed that it is possible to include tortuosity using a supplementary

171 fractal scaling law for the pore length L_0 [53–58].

As for the porosity, the permeability of the FPM is a function of the pore-size interval $[R_m; R_M]$, 172

fractal dimension *D* and also on the dimension of the REV L_0 . Yet, remembering that $L_0 \propto R_M$ and 173 that $R_M \gg R_m$ it becomes obvious that $K_e \propto R_M^2$. This result is not surprising as it appears 174

similar to the model proposed by Katz & Thompson based on percolation theory [59,60]:

175

176
$$K_e = \frac{F}{226} d_c^2 \propto d_c^2 \tag{18}$$

where *F* is the formation factor (
$$0 < F < 1$$
) that accounts for pore structure conformation and
tortuosity and d_c is the critical pore entry diameter that corresponds to the inflexion point in the
intrusion curve obtained using MIP. In other words, d_c is the greatest pore diameter that allow

entry to the porous network and it seems reasonable that $d_c \approx 2R_M$. 180

181 Also note that equation (17) can alternatively be rewritten to include porosity \emptyset as suggested by 182 Guarracino [61], this presents the major advantage to flush the cumbersome parameter L_{0} :

183
$$K_e = \frac{\emptyset}{8} \left(\frac{2-D}{4-D} \right) \left(\frac{R_M^{4-D} - R_m^{4-D}}{R_M^{2-D} - R_m^{2-D}} \right) \implies K_e \propto \emptyset R_M^2$$
(19)

185 **3.4. Relative permeability**

- 186 Mualem's model [38] was used to evaluate the relative permeability k_r of the FPM (eq. 4). Even
- 187 though the equations used here are quite simple, it was not possible to derive an analytical
- expression for the function P(S); because of the two different exponents (2 D) and (1 D) in eq 14). Alternatively, k_r was evaluated using the trapezoidal rule of Riemann sums following the
- original proposition of Mualem [38,62]. The saturation interval [0;1] was discretized into n =
- 191 10^4 intervals forming a non-uniform grid with $u_0 = 0$ (dry state) and $u_n = 1$ (saturated state)
- 192 and the numerator in eq. (4) then wrote:

193
$$\begin{cases} \int_{0}^{S} \frac{du}{P(u)} = \sum_{i=1}^{m} (u_{i} - u_{i-1}) \left(\frac{1}{P_{i}} + \frac{1}{P_{i-1}}\right) \\ with \ 1 \le m \le (n-1) \mid S = u_{m} \end{cases}$$
(20)

- 194 where u_i is the saturation value of the *i*th interval of the non-uniform grid and P_i the
- 195 corresponding value of the water pressure (MPa).
- 196 It is obvious that $P_n^{-1} = \infty$, so the denominator in eq. (20) cannot be evaluated numerically. To 197 overcome this difficulty, the surface area of the last trapezoid was not accounted in the
- 198 summation and the relative permeability was then calculated as follows:

199
$$k_r(S) = \sqrt{u_m} \left[\frac{\sum_{i=1}^m (u_i - u_{i-1}) \left(\frac{1}{p_i} + \frac{1}{p_{i-1}} \right)}{\sum_{i=1}^{n-1} (u_i - u_{i-1}) \left(\frac{1}{p_i} + \frac{1}{p_{i-1}} \right)} \right]^2 \text{ with } 1 \le m \le (n-1)$$
(21)

- 200 The quality of the numerical approximation was tested by comparing the relative permeability
- 201 curves evaluated using eq. (21) to those obtained using usual MVG analytical equation (eq. 5).
- 202 The results are presented in Figure 2. The numerical approximation scheme did provide an
- almost perfect match with the analytical equation despite the fact that one trapezoid surfacearea was neglected.
- 205



206 207

Figure 2: comparison between numerical approximation (eq. 21) and MVG analytical equation (eq. 5)

209 **4. Results**

210 4.1. Water retention

Figure 3 presents some water retention curves that were obtained for the FPM using eq. (14)and the following data:

- the minimal pore radius R_m was assumed to be constant and equal to the monolayer 214 thickness to allow the edification of a monolayer in the smallest pores ($R_m = t_m = 3 \times 10^{-10}$ m);
- the maximal pore radius R_M was varied between 10 nm and 1 μ m (1 × 10⁻⁸ m ≤ R_M ≤ 1 × 10⁻⁶ m);
- the fractal dimension was varied between 1.1 and 1.9 (1.1 < D < 1.9).

219 The reader can observe that the water retention curves of the virtual FPM are of type IV [63] and 220 that they are guite similar to the desorption isotherms of common cement-based materials [64– 221 68]. Figure 3(a) underscores the influence of the fractal dimension *D* and Figure 3(b) the influence of the maximal pore radius R_M . Increasing the fractal dimension D mainly results in 222 223 increasing the saturation value at low RH (*i.e.* the monolayer) because it controls the pore 224 number distribution and the thus the relative contribution of the smaller pores (Figure 1). The maximal pore radius R_M exhibits two distinct effects: firstly decreasing the value of R_M increases 225 the length of the plateau at high RH through Kelvin equation (7) and secondly changing the value 226 227 of R_M also impacts the pore number distribution (and then the contribution of the smaller pores) 228 through equation (1).

229





231

230

232 All the water retention curves were fitted using van Genuchten equation (18) using a classical 233 least-square minimization process. It must be mentioned here that, despite its deemed great 234 adaptability, van Genuchten equation (2) did not provide a good fit for all the water retention curves. This was particularly obvious with small values of R_M that generated large plateaus at 235 236 high RH that could not be described using van Genuchten (Figure 4), because van Genuchten 237 implicitly assumed that the pore size distribution is unbounded and that S = 1 only when $P \rightarrow P$ 238 ∞ . Actually, this observation proved to be valid for all the tested cases (Figure 12), this was 239 already observed and discussed elsewhere [62].



Figure 4: examples of poor fits obtained using van Genuchten equation

242 243

241

244 The values of the two parameters P_0 and m were found to depend on both fractal dimension D245 and maximal pore radius R_M (Figure 5) but further examination of these results unexpectedly 246 showed that the exponent *m* was more or less a function of the fractal dimension *D* alone and 247 that the pressure P_0 was a function of the maximal pore radius R_M alone (Figure 6). Roughly speaking, the *m*-exponent is a measure of the fractal dimension ($m \propto -D$) whereas the bubbling 248 pressure P_0 is a measure of the bigger pores dimension ($P_0 \propto R_M^{-1}$). This result is surprising 249 250 because van Genuchten equation was proposed to provide an analytical solution to Mualem's model without any physical basis. Note that the similarities between van Genuchten model and 251

fractal approaches were already noted and discussed by Hunt [69].

253





256

To go further in studying the "fractal nature" of van Genuchten equation, Figure 7 depicts the influence of the two parameters m and P_0 on the water retention curve. It is plain to see that mmainly controls the saturation at low RH (Figure 7-a) as is the case with the fractal dimension D(Figure 3-a). The same holds true for the pressure P_0 (Figure 7-b) and the maximal pore radius

261 R_M (Figure 3-b) that generate a plateau at high RH and also impact the saturation at low RH.

262





264

263

265 4.2. Intrinsic permeability

Figure 8 shows that the intrinsic permeability K_e of the FPM (eq. 17) was ranging between 266 267 10⁻¹⁸ m² and 10⁻¹⁵ m². Despite the fact that no tortuosity was introduced in the description, the latter results did present the same order of magnitude as the permeability values measured 268 269 using gas [70–72]. The reader should keep in mind that the values obtained using water are 270 much lower than using gas [70,73]. This may be due to the change in microstructure induced by 271 the drying (necessary for the gas permeability tests) [74,75] and also to electrical interactions 272 between the solvent (water is a polar molecule) and the pore walls that limit the mobility of water and then decreases permeability [76–80]. As for tortuosity, water-substrate interactions 273 274 were not accounted for here; so gas permeability results were the most appropriate to compare 275 with.





Figure 8: influence of D and R_M on the intrinsic permeability K_e of the fractal porous medium

280 Examining Figure 8, it is plain to see that the intrinsic permeability K_e of the FPM is mostly 281 influenced by the maximal pore radius R_{M} . Remembering that the pressure P_{θ} was a measure of

 R_M then a relation between K_e and R_M should exist: $K_e \propto P_0^{-2}$. Note that this was already noted 282

283 and verified by Guarracino [61] for a large soil dataset.

284 In an attempt to check the existence of such a relation for cement-based materials, some 285 permeability results obtained using inverse analysis were plotted in Figure 9 and some piece of corresponding information was reported in Table 1. It is plain to notice that all the results were 286 287 obtained by the same author: it was a deliberate choice (but this could called into question) not 288 to include the results obtained by other researchers because it would have induced too much 289 scatter as inverse analysis is known to be a highly sensitive method [36,62]. Also note that the 290 results also include data obtained using the cup-method as it was shown to give similar results 291 to inverse analysis [81]. The results include non-carbonated and carbonated concretes and 292 pastes that yielded variations in P_0 and K of two and four orders of magnitude respectively.

All the points almost align along the curve $K(P_0) = AP_0^{-2}$ (with $A \approx 3.0 \times 10^{-19} \text{ m}^2$) but with 293 some scatter that remained encouragingly less than one order of magnitude. It must be recalled 294 295 that the method proposed by Katz and Thompson [59,60] that is commonly used to evaluate the intrinsic permeability based on MIP tests [82-84] is known to present large differences (up to 296 297 two orders of magnitude for low-permeable materials) [85–88]. Of course, there are not enough 298 data to judge the existence and quality of the proposed correlation and more results would be 299 necessary and the readers are invited to test this correlation using their own results. Yet, such a 300 correlation would be very useful because it would allow the intrinsic permeability to be 301 estimated using the water retention curve (similarly to the relative permeability through 302 Mualem model) and then reduce the number of tests needed to characterize the water transport 303 properties. Finally, the reader should keep in mind that such a correlation would be fluid dependent.

- 304
- 305
- 306

Table 1: permeability results plotted in Figure 9

Reference	Materials	Composition/remarks	Method
Poyet et al. (2011) [36]	Concrete	Old concrete, highly porous and permeable Unknown composition	Inverse analysis
Drouet et al. (2015) [89]	Paste	4 different binders, w/c = 0.40	Inverse analysis
Auroy et al. (2015) [81]	Paste	Same pastes as Drouet et al. (2015) [89]	Inverse analysis + cup-method
Poyet et al. (2019) [90]	Concrete	Low permeable OPC concrete (w/c = 0.42)	Inverse analysis





Figure 9: intrinsic permeability K versus P₀, from [36], [89], [81] and [90]



311 4.3. Relative permeability

312Figure 10 compares the relative permeability of some fractal porous media obtained using313Mualem's model (eq. 4) to those obtained using van Genuchten equation (eq. 5). For the sake of314clarity, only three values of D (1.1, 1.5 and 1.9) are displayed and for each five values of R_M (10-8,315 2×10^{-8} , 5×10^{-8} , 10^{-7} and 10^{-6} m). It was clear that the relative permeability k_r of the FPM (Figure31610-a) was a function of D and R_M , although the fractal dimension appeared to be the most317influential parameter. It should be mentioned that the unusual change of slope occurring in318some curves below 0.4 in saturation (D = 1.9) was due to the strong knee that was obtained for

319 small R_M values (see Figure 3 and Figure 4).

320 The use of van Genuchten equation (Figure 10-b) did not appear to be satisfactory as it clearly 321 led to underestimate the k_r values (Figure 11). This underestimation was due to the limited 322 fitting ability of van Genuchten equation that was not able to perfectly fit the water retention 323 curves of all the FPM. This was already noted for small R_M values because of the plateau at high 324 saturation (Figure 4) but this conclusion was found to be valid in all cases, even for high values 325 of R_{M} . The isotherms obtained using van Genuchten all showed differences with those of the FPM (Figure 12) even though they could not be detected using the naked eye in most cases. The point 326 327 was that these differences, even small, were responsible through Mualem's model, of the 328 underestimation by one order of magnitude that was observed in Figure 11. This last point is 329 important because it sheds light on the subject of the permeability of cement-based materials and more specifically on the fact the permeability values to be used in simulations (through 330 inverse analysis) are smaller than those measured using water [39]. Part of these differences 331 332 might be explained by vanGenuchten equation and its limited fitting ability because inverse 333 analysis is known to be very dependent on the input data and the models that are used [62].







 $\begin{array}{l} 339\\ 340 \end{array} \textit{Figure 11: comparison between the } k_r \textit{ values obtained using the numerical approximation (eq. 21) or the MVG analytical equation (eq. 5) \end{array}$



Figure 12: comparison of the capillary curves obtained of the virtual FPM (eq. 14) and fitted using van Genuchten
 equation (eq. 2)

346 **5. Conclusion**

- 347 The pore-structure of cement-based materials is more and more recognized as being fractal. The
- 348 mathematical meaning of fractality is the existence of a simple analytical pore scaling law (in the
- form of a power function). Using this scaling law and considering a single fractal dimension, it
- 350 was easy to generate virtual and simple fractal porous media that were then used to study some 351 important water transport properties (intrinsic and relative permeability and water retention
- 352 curve) and the associated Mualem model and van Genuchten equations. It must be recalled here
- 353 that due to their simplicity (single fractal dimension) the virtual fractal porous media may not be
- 354 representative of the real cement-based materials.
- Firstly, van Genuchten equation was used to fit the capillary curves that were generated
- 356 considering physical adsorption and capillary condensation. It appeared that, although bereft of
- any physical basis, van Genuchten equation may be considered as bearing some physical
- information because its two parameters were closely related to the fractal porous media
- properties: the exponent *m* was a measure of the fractal dimension (*D*) whereas the pressure P_0
- 360 was a measure of the maximal pore radius (R_M) .
- 361 Secondly, the capillary curves were used to evaluate the relative permeability (making use of
- 362 Mualem model). Although it is known to be flexible, van Genuchten equation did not provide
- 363 perfect fits and the differences between the fitted capillary curves and those of the fractal porous
- 364 media were sufficient to generate significant error: the relative permeability values were
- 365 systematically underestimated up to one order of magnitude. This partly explains why the
- intrinsic permeability values obtained using inverse analysis are always lower than the
- measured ones. This also confirms the strong dependence of inverse analysis upon the modelsand data used.
- soo anu data used.
- 369 Finally, the equations regarding permeability of the fractal porous media suggested that there
- 370 should exist a relation between the intrinsic permeability and van Genuchten parameter P_0 .
- Analysis of some results of the author tended to confirm the existence of such relationship even
- though the number of results are not sufficient to conclude. Such a relationship would prove
- extremely useful because it could help reducing the number of tests needed to describe watertransport.
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- 375

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- 379

380 6. Bibliography

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606	Nomenclature		
607	•	R_m minimal pore radius (m)	
608	٠	R_M maximal pore radius (m)	
609	٠	D fractal dimension (without unit)	
610	٠	N cumulated number of pores (without unit)	
611	٠	r pore radius (m)	
612	٠	<i>n</i> number of pores of radius <i>r</i> (without unit)	
613	٠	Ø porosity (without unit)	
614	•	S saturation ratio (without unit)	
615	•	S_a saturation ratio due to adsorption (without unit)	
616	•	S_c saturation ratio due to condensation (without unit)	
617	•	<i>P</i> liquid water pressure (Pa)	
618	•	t time (s)	
619	•	<i>K</i> intrinsic permeability (m ²)	
620	•	k_r relative permeability to water (without unit)	
621	•	η dynamic water viscosity (Pa s)	
622	•	<i>m</i> constant of van Genuchten equation (without unit)	
623	•	P ₀ constant of van Genuchten equation (Pa)	
624	•	t_w thickness of the water layer adsorbed on the pore walls (m)	
625	•	t_m thickness of the water monolayer (m)	
626	•	k constant of Langmuir model (without unit)	
627	٠	h relative humidity (without unit)	
628	•	r_{K} Kelvin radius (m)	
629	•	<i>M</i> water molar mass (kg/mol)	
630	•	σ water surface tension (N/m)	
631	•	ho water density (kg/m ³)	
632	•	<i>R</i> universal gas constant (J/mol/K)	
633	•	<i>T</i> absolute temperature (K)	
634	٠	q flowrate through a pore of radius r (m ³ /s)	
635	•	Q_t flowrate through all the pores (m ³ /s)	
636	•	ΔP pressure difference applied to the pores (Pa)	
637	•	F formation factor (without unit)	
638	•	d_c critical pore diameter (m)	