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Experimental assessment of the variability of concrete air permeability: repeatability, reproducibility and spatial variability

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Abstract

To study the effect of spatial variability of some influential parameters on the durability of the building envelopes, some important information are required: the mean, the standard deviation and the spatial correlation of the studied fields defined by the correlation lengths. In this paper, the characterization of the concrete spatial variability was performed which included a significant number of test allowing the characterization of concrete air permeability. For this a concrete wall of 2 m of height, 1.20 m of width and 15 cm of thickness was manufactured in laboratory in which concrete specimens were periodically taken and tested. Firstly, results repeatability was performed. For these purpose, three tests per sample was carried out in order to assess the repeatability of the measurements. Secondly, the reproducibility of the measurements was carried out by testing two samples for each cored specimen.
Good repeatability of the intrinsic permeability measurements on each tested sample is recorded. Indeed, the standard deviation does not exceed 0.67×10^{-17} m². Also, the concrete intrinsic permeability depends on the spatial location of the studied sample. It was found to be ranging between 2.38×10^{-17} and 5.91×10^{-17} m² with an average value equal to 3.66×10^{-17} m².
The obtained results enable to quantify the spatial variability of concrete air permeability, particularly in terms of mean value and standard deviation. Also, it allowed highlighting the spatial correlation length of the studied fields and for probabilistic approaches regarding the prediction of the concrete durability.

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Keywords: Concrete, air permeability, spatial variability, statistical function, correlation length

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1. Introduction

The cementitious materials, which are nowadays the most used building material, have a very complex microstructure with heterogeneous shape leading to random mechanical and physical properties. These properties are affected by different phenomena that have chemical origin such as the cement hydration or physical such as the moisture, heat and aggressive species transfers. These latter can vary considerably depending on how the concrete is manufactured, cast and conditioned. This variability will affect the material behavior in general and, particularly, his behavior regarding the transfer phenomena.

Some works have highlighted the effect of the variability of some concrete parameters on its behavior. De Larrard [1] has studied the influence of this variability on leaching of concrete and its service life when it is used for manufacturing tunnels for radioactive waste storage. They showed the interest of considering this properties variability of cementitious materials.

The present work focuses on the study of the spatial variability of concrete air permeability. This will be used in probabilistic approaches for the prediction of hygrothermal behavior and durability. Trabelsi et al. [2] have studied the statistical variability of water vapor desorption isotherms. They showed their impact on the concrete drying and noticed a significant effect especially in the concrete cover. Dominguez-Minoz et al. [3] have studied the thermal conductivity of foams and noticed an important variability of this property. They compared other results provided by an inter-laboratories study on the hydric properties. They noticed a good reproducibility for some properties (porosity and density) when this reproducibility remains very poor for other properties such as the sorption isotherms and the resistance to the water vapor despite the used techniques are the same for the different laboratories. Feng et al. [4] studied the repeatability and the reproducibility of hydric properties of different materials. They concluded to a good repeatability for their results, nevertheless, the reproducibility was poor when comparing the results obtained by different laboratories. Indeed, significant differences are reported for the transport properties due to differences of the experimental procedures and analyses monitoring conditions, when comparing the results obtained by different laboratories [3, 5-7].

The study is conducted on a concrete wall. This wall was cored at different spatial locations in order to obtain different samples. The obtained samples were used for the characterization of air permeability of this concrete. A statistical distribution laws are proposed for the description of the variability of this property. Also, repeatability and reproducibility of the results are performed.

2. Experimental program

To study the effect of spatial variability of some influential parameters on the hygrothermal behavior of the building envelopes, some important information are required: the mean, the standard deviation and the spatial correlation of the studied fields defined by the correlation lengths. To obtain this data, an experimental concrete wall of 2 m of height, 1.20 m of width and 15 cm of thickness was manufactured in the laboratory in which samples were cored following six vertical lines. Two lines are dedicated to air permeability tests (diameter=65 mm, height=50 mm) (lines B and E in Fig. 1).

Fig. 1. Specimen position in the experimental concrete wall

The used concrete was prepared with Portland-cement of type CEM I 52.5 N with 95% part of clinker. It was prepared in according to the EN 206-1 standard. Its composition is reported in Table 1.

Table 1. Composition of concrete

Constituents	$kg.m^{-3}$
Cement CEM1 52.5N	350
Gravel 10/14	1201
Sand 0/4	762
Water	211.8
Superplasticizer	7

3. Results and discussion

To study the spatial variability of air permeability of the concrete composing the wall, this latter was cored periodically following the two lines B and E in order to obtain cylindrical specimens which were, then, sawn to have samples of 65 mm diameter and 50 mm thick. To verify the reproducibility of the measurements, two samples were produced by cored specimen. In this way 36 samples were obtained to perform the measurements. To unsure a radial tightness of the samples a mono-directional flow of the air and, each sample was laterally surrounded by a resin ring of about 15 mm thick.

The permeability measurement was performed using a fully automatic device composed by a “Thermicar permeameter” and a data acquisition interface. The followed method is a transitory method which principle is described by Fig. 2.

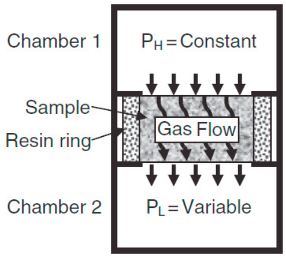

Fig. 2. Schematic view of the air permeability device principle

During the measurement, carried out following the procedure described by Hamami *et al.* [8], the sample is placed between two pressure chambers and submitted to a pressure gradient. This one is generated by applying several levels of a high pressure PH, which is kept constant (equal to one of these values: 130 – 160 – 190 – 210 and 350 kPa), at the upstream of the sample and a low pressure P_L, initially equal to 8.5 kPa, at the downstream. This low pressure varies according to the air flow through the sample.

For each high pressure applied, an apparent permeability “K_A” is obtained according to a modified Darcy’s law (eq. 1). The intrinsic permeability “K_{INT}” of the material is then calculated according to Klinkenberg [9] approach (eq. 2) which is based on the evolution of this apparent permeability “K_A” as a function of the inverse mean pressure P_m (Eq. 3) (Fig. 3). More detailed description of the used method is given by Hamami *et al.* [8].

$$K_A = \frac{2\mu L}{P_H^2 - P_L^2} V_L \frac{dP_L^2}{dt} \tag{1}$$

μ [Pa.s] is the air dynamic viscosity, V_L [m^3] is the volume of the low pressure chamber (at the downstream of the sample) and L[m] is the sample thickness.

$$K_A = K_{INT} \beta \frac{1}{P_m} + K_{INT} \tag{2}$$

β [Pa] is the Klinkenberg factor which represents the air slip at the interface of the material pores.

$$\frac{1}{P_m} = \frac{2}{P_H + P_L} \tag{3}$$

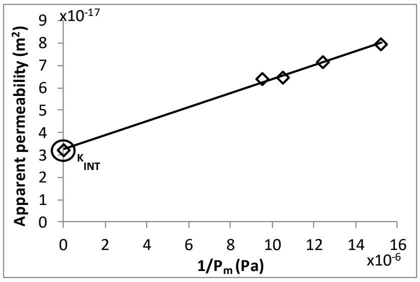

Fig. 3. Intrinsic permeability determination according to Klinkenberg approach

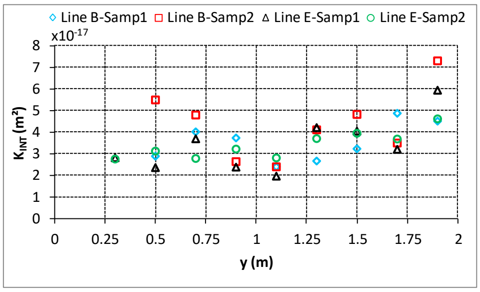

Fig. 4. Intrinsic permeability following the vertical lines B and E

The results of the intrinsic permeability of the two vertical lines B and E are shown on the Fig. 13. In order to properly quantify the spatial variability of the intrinsic permeability, the repeatability and reproducibility of the measurement were studied. For these purposes, three tests per sample was carried out in order to assess the repeatability of the measurements and, as previously indicated, two samples were tested for each cored specimen to assess the reproducibility of the measurements. Obtaining more than two samples of 50 mm thick per cored specimen was impossible since the thickness of the wall is equal to 150 mm (which correspond to the specimen height) and the use of more thin concrete samples (less than 50 mm thick) cannot be considered because of the device specifications. The statistical data corresponding to the results presented in Fig. 4 are reported in Table 2 (by averaging the average value of the reproducibility tests).

Table 2. Statistical data of the air permeability for the two vertical lines B and E

	Average x10^{-17}	Standard deviation x10^{-17}	Coef of variation (%)	Min x 10^{-17}	Max x10^{-17}
Line B	3.95	1.03	26.20	2.39	5.91
Line E	3.40	0.89	26.50	2.38	5.28
Both lines	3.66	0.97	26.7	2.38	5.91

The obtained results give a good repeatability of the intrinsic permeability measurements on each tested sample. Indeed, the standard deviation does not exceed 0.67x10^{-17} m².

Concerning the reproducibility assessment, the results presented in Fig. 5 give a comparison between the measured values of the intrinsic permeability of the two tested samples per location. Each value corresponds to the average of the three values measured on the same sample.

This Fig. 5 shows that, on the one hand, an important variation is observed for the intrinsic permeability measured on two samples from the same location (B2) and, on the other hand, permeability that remain constant for the two tested samples (B5). Globally, this figure shows that the intrinsic permeability depends on the spatial location of the studied sample. The permeability decreases at the middle of the vertical line, increases a little near to the bottom of the wall and is more important at the top of this one.

Considering these observations, one can expect that the spatial variability will be of an important impact on the wall permeability. To bring more clarifications to this question, the spatial distribution of the intrinsic permeability is associated to statistic distribution laws in order to identify the different parameters governing the spatial variability of this concrete property (Fig. 6).

Fig. 6 shows the variability extent of the intrinsic permeability observed on the 36 tested samples and the fitted probabilistic laws associated to this variability. The different data for the studied distribution laws are given by Table 3. The Normal and Weibull laws seems to be the most appropriated to reproduce the statistic distribution of the experimental values. These two laws present the same average of 3.65x10^{-17} m² and a variance of 0.95x10^{-34} m^4 and 1.04x10^{-34} m^4 respectively for the Normal and Weibull law.

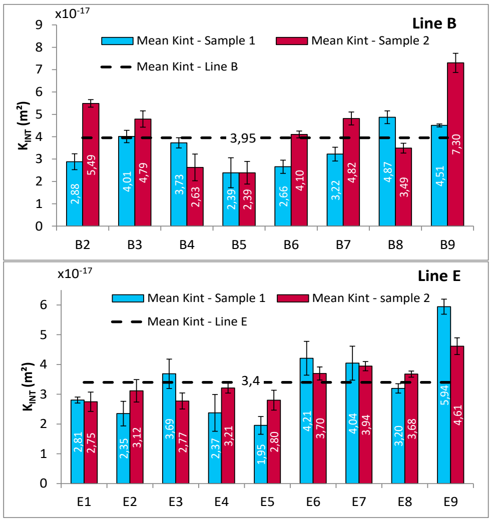

Fig. 5. Intrinsic permeability measurements reproducibility following the lines B & E

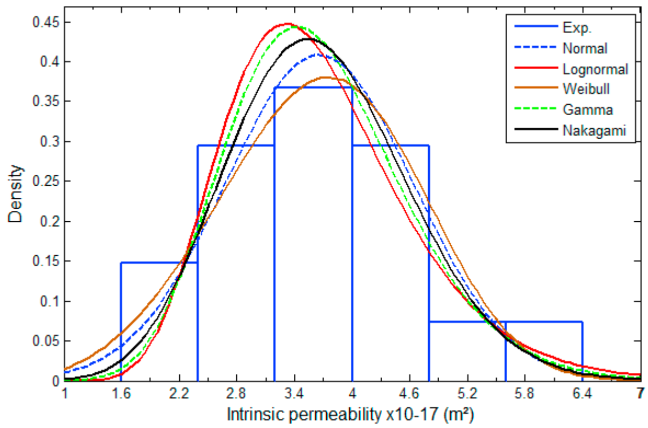

Fig. 6. Intrinsic permeability distribution for concrete. The lines are the fitted proposed probabilities density

Table 3. Statistic data associated to the proposed distribution laws

Distribution Law	Normal	Lognormal	Weibull	Gamma	Nakagami
Average x10-17	3.65	3.66	3.65	3.65	3.66
Variance x10-34	0.95	0.94	1.04	0.85	0.86

The concrete intrinsic permeability (by just averaging the air permeability value of the repeatability test results) was found to be ranging between $1.95x10^{-17}$ and $7.3x10^{-17}$ m^2 with an average value equal to $3.65x10^{-17}$ m^2. This is in good agreement with the results obtained by [7, 10]. The results variability is reduced in the case where the reproducibility test is taken into account by averaging the average value presented in the Fig . In this case the concrete intrinsic permeability was found to be ranging between $2.38x10^{-17}$ and $5.91x10^{-17}$ m^2 with an average value equal to $3.66x10^{-17}$ m^2.

In order to perform hygrothermal and durability simulations using probabilistic approach taking into account spatial variability of the inputs parameters, it is necessary to know the spatial correlation of the studied property field. This is defined by the correlation length noted “Lc” which may enable to estimate the distance between two testing points at which the measured values become independent. It reflects the importance of the random field spatial correlation used in the probabilistic approach implementation. The higher the correlation length, more the field is strongly correlated [3]. This parameter is identified using a variogram based on the experimental value previously presented. The variogram is a practical mean for describing the spatial correlation of measurements. On one hand, it is a tool to investigate and quantify the spatial variability of the phenomenon under study. On the other hand, most geostatistical estimation or simulation algorithms require an analytical variogram model, which can be derived from the experimental variogram [11, 12]. The variogram at the lag distance “d” is expressed as follows (Eq. 4).

$$\gamma(d) = \frac{1}{2|N(d)|} \sum_{(i,j)\,\epsilon\, N(d)} |Y_i - Y_j|^2 \qquad (4)$$

Where $N(d) = \{(i,j)\backslash |x_i - x_j| = d\}$

$\gamma(d)$ is the variogram value; Y_i is the value of the studied property at the x_i position; N(d) is the set of pairs of points (i, j) such that the distance between these points is equal to d (number of pairs that satisfy this condition).

The relationship between the covariance (C) and the variogram is defined by Eq. 5. Remember that the covariance on 0 is the variance. By knowing the variogram value corresponding to each distance, we can deduce from Eq. 5 the value of the covariance. Then, it is enough to optimize the value of correlation length “Lc” in the covariance functions which can be expressed as follows (Eq. 6):

$$\gamma(d) = C(0) - C(d) \quad (5)$$

$$C(x,y) = \sigma^2 \exp\left(-\frac{\|x_i - x_j\|^2}{L_c^2}\right) \quad (6)$$

Where C(x,y) is the covariance between the two points x_i and x_j. Each term C_{ij} of the covariance matrix "C" is the value of the covariance function calculated between the nodes i and j of the mesh. The vectors x_i and x_j give the position of the corresponding nodes.

Fig. 7 shows a comparison between the covariance values measured on the experimental concrete wall and those obtained using the corresponding covariance functions. As indicated previously, the air permeability was evaluated according to two lines (B & E). It is presented on the y-axis the normalized covariance relative to the variance. It is observed that the correlation length is of the order of the meter.

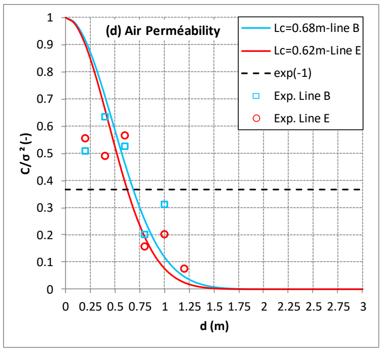

Fig. 7. Correlation length identification of the air permeability

4. Conclusion

The main of this work is to characterize spatial variability of some influential parameters on the prediction of the hygrothermal behavior and concrete structure durability. For this, an experimental wall concrete is built in the laboratory. Several specimens are cored periodically and tested to evaluate the spatial variability of the air permeability. It is found Good repeatability of the intrinsic permeability measurements on each tested sample is recorded. Indeed, the standard deviation does not exceed 0.67×10^{-17} m². Also, the concrete intrinsic permeability depends on the spatial location of the studied sample. It was found to be ranging between 2.38×10^{-17} and 5.91×10^{-17} m² with an average value equal to 3.66×10^{-17} m². The correlation length of the air permeability is of the order of the meter. It was found to be ranging from 0.62 to 0.68 m.

The results obtained do however constitute a database that can be used as inputs for probabilistic approaches. It can be used by considering the fitting probabilistic laws or as inputs for generating random fields by using, for example, Karhunen Loeve decomposition.

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