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Assessment of liquid water and gas permeabilities of partially saturated ordinary concrete

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HIGHLIGHTS

- The evolution of the permeability of partially saturated ordinary concrete is studied as a function of degree of saturation.
- An experimental procedure is provided for the measurement of liquid water permeability of concrete partially saturated.
- The sample size is a parameter which can influence on the assessment of the permeability of concrete.
- Existing models to predict the relative permeability fits imperfectly the experimental results for different sample sizes.
- The preconditioning applied has a great influence on measurement of the permeability of concrete.

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ABSTRACT

The durability of concrete depends on its ability to prevent the ingress of aggressive chemical species. Transport properties of concrete, mainly permeability, play a key role in assessing and predicting the durability of reinforced concrete structures. The hydric state affects the transport parameters like permeability which has a large influence on the penetration of aggressive agents and so on durability of concrete. This paper presents an experimental study on relative gas and water permeabilities of ordinary concrete versus its saturation degree. The experimental results give the measurements of liquid water and gas permeabilities of concrete samples with different sizes as well as those of the degree of saturated liquid water obtained by mass weighing. The analysis shows the influence of the saturation degree of concrete on the variation of water and gas permeabilities. Validation of Van Genuchten–Mualem law for porous media has been verified for ordinary concrete (OC). Moreover, this study highlights the effect of drying temperatures on the intrinsic gas permeability of concrete.

1. Introduction

The presence of aggressive fluids and their transport is the most important factor controlling the durability of cement materials [1]. In concrete structures, the durability of concrete and corrosion of reinforcing steel are intimately linked to the permeability of exposed concrete surfaces [2]. Therefore permeability, defined as the movement of fluid through a porous medium under an applied pressure load, is the most important property of concrete governing its long-term durability [3]. Water and gas permeabilities of concrete are then major indicators to evaluate the ability of this material to prevent the penetration of aggressive agents such as carbon dioxide (CO_2) or chlorides as well as the transfer of water vapor due to drying of the material.

For more than a century, Darcy's coefficient of permeability has been used as a measure of concrete tightness from which its durability is often derived [4]. As reported by Darcy, the permeability is measured in water saturated materials; yet the reality is that the concrete material undergoes fluctuations in its humidity level over time in relation to its environment. The hydric state of concrete is so important because, according to the saturation rate of the material, different pore sizes are available [5]. Therefore, measuring the permeability is influenced by the moisture content of the material [6]. Thus, saturation rate plays a fundamental role in the transport properties, for example, the gas permeability of a specimen of concrete increases when the degree of saturation decreases [6].

Many advances have been made in recent years in understanding the evolution of the permeability of concrete especially under different loads. In the absence of a standard testing method, the techniques devised to study the effect of mechanical stress on the permeability of concrete may be classified on the basis of:

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the permeameter, load configuration and instance the permeability is measured [1]. Indeed, Picandet [7,8] carried out a series of tests on cylindrical specimens of 5 cm thick, in which he studied the influence of moisture and damage (measurements after mechanical loading) on the gas (nitrogen) permeability of concrete. It showed a relationship between the gas permeability and damage. Then, Banthia and associates [3,9–11] studied the effect of load level, load history and fibers blends on the water permeability of concrete which was measured on hollow cylindrical cores during compression in steady state flow condition. Then, Choinska [12,13] studied the evolution of the dry gas permeability of concrete under compressive loading (measured in the presence of load) in pre-peak and post-peak by varying the temperature of dry hollow cylindrical specimens. By an experimental study, Aubernon [14] determined the evolution of the water vapor nitrogen permeability of concrete under high temperature and different mechanical loading (pre-peak and post-peak) and after unloading. Indeed, we are able to apply on a dry concrete sample mechanical and thermal loading and to measure permeability. However, we do not currently know the evolution of the permeability of concrete at different water contents of the material. Coussy et al. [15] have shown that a change in physical–mechanical properties of cementitious materials strongly depends on their degree of saturation.

Few experimental results exist concerning the relative permeability of cement-based materials to gas (K_{rg}) and even less concerning the relative permeability to liquid water (K_{rl}). The influence of the saturation rate on the intrinsic gas permeability has been studied experimentally by Villain et al. [6]. In this study, the Klinkenberg method [16] (see Section 2.2) was applied for different saturation rate to obtain the intrinsic gas permeability at a given degree of saturation (S_l).

From a comparison of gas and water permeabilities, it is clearly noted that gas permeability measurement requires less time and produces more reproducible results. However, an accurate and reproducible measurement of the permeability coefficient with water becomes tedious and very difficult to perform as the quality of concrete improves [4]. Regarding this difficulty of the experience, measurements of the liquid water permeability of concrete are not routinely performed and few experimental data are available with regards to the relative permeability of cement-based materials to liquid water. The conventional method to measure permeability is to apply a pressure gradient over a specimen (application of a liquid pressure in laminar flow conditions) and measure the flow. Therefore, the permeability can be calculated from Eq. (7) when the steady-state regime is reached. But, this may take days or weeks for good quality concrete [17], and the sample may evolve during that time (due to hydration and/or leaching) [18]. Moreover, there is a high risk of leaks under pressure that can be difficult to detect. Thus, the permeability depends on the characteristics of the fluid, the pore network and other voids (microcracks, paste-aggregate interfacial zone, etc.) of the material, and also on the hygral state of the test specimen [19].

To overcome this difficulty, analytic expressions are proposed in the literature, for example, Eq. (1) which predicts the hydraulic conductivity from the statistical pore size distribution. This formula has been derived by Van Genuchten [20], based on the model of Mualem [21]:

$$K_{rl}(S_l) = \sqrt{S_l}\left(1-\left(1-S_l^{1/m}\right)^m\right)^2 \quad (1)$$

In addition, the author proposed a methodology to estimate the parameters of this equation, by using the fitted expression. Thus, the parameter m is the exponent appearing in the capillary pressure curve of Eq. (12) (see Section 3.1).

In the particular case of cement-based materials, Savage and Janssen [22] have shown the relevancy of this new expression of Van Genuchten–Mualem (V.G.M) (Eq. (1)), originally developed for soils, to account for the liquid–water movement in unsaturated Portland cement concrete. This formula (Eq. (1)) has been applied to different cement pastes and different concretes (ordinary and high performance) as part of the modeling of drying [23,24] and in particular, in the context of the thesis of Mainguy [25] who presented a model with macroscopic scale of isotherms hydric transfers, based on the thermodynamic approach of mass transfer in continued porous media, developed by Coussy [26].

As in the case of the relative permeability to liquid water (K_{rl}) and similarly as for most capillary porous materials, the relative gas permeability (K_{rg}) of concrete may be described from the analytic expressions given by Luckner et al. [27] based on the model of Mualem [21]:

$$K_{rg}(S_l) = (1-S_l)^q \cdot \left(1-S_l^{1/m}\right)^{2m} \quad (2)$$

In this study, Eq. (2) has been applied with the values of parameter m equal to 0.5 which is a mean value of several experimental results from the literature, obtained with ordinary concretes and with different values of parameter q. According to Parker et al. [28], in the case of soils, when extending Mualem's model [21] to the nonwetting phase, this parameter q equal to 0,5. Moreover, Monlouis-Bonnaire et al. [29] has proposed for the assessment of the relative gas permeability of cement-based materials an adjustment with a value of parameter q equal to 5.5. So, in this study, Eq. (2) has been also verified with this value of q proposed by Monlouis-Bonnaire for the adjustment of the model of Van Genuchten–Mualem (V.G.M).

This paper is devoted to the assessment of transport properties, such as water and gas permeabilities, which are identified as the durability indicators of concrete structures [30]. The results of an experimental study on the measurement of the relative water and gas permeabilities of ordinary concrete, subjected to different liquid water saturation states (intermediary between the saturated state and the dry state) are presented here. To achieve this objective, concrete was characterized by its intrinsic permeability and the evolution of this parameter was studied as a function of the saturation degree of the material. In this study, different temperatures were used to dry the concrete specimens, so the evolution of gas permeability according to different drying temperatures is also a part of our results.

On the other hand, this study was carried out with the aim to highlight the effect of the size of the specimen (size effect) on the measurement of concrete gas permeability as a function of the saturation degree.

In the absence of a standard testing method, the techniques devised to study the gas permeability may be classified on the basis of: (i) the permeameter, (ii) load configuration and (iii) instance the permeability is measured. In the literature, several researches were carried out on the determination of the gas permeability of cementitious materials using also various methods of measurement that are currently available like the pulls test method or the "CEMBUREAU" equipment (with constant load). For hardened concrete, gas permeability is often measured in the laboratory (on specimens or core samples taken from a structure). Accordingly, one finds reports on the water and gas permeability using tested samples with different sizes. A summary of the various tested samples with different sizes is presented in Table 1. The question arises here is that, if the samples tested in different research done until today, had not the same size, is there an effect of the size of sample tested on the measurement of permeability of the material?