Cement and Concrete Research 89 (2016) 109–119

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: www.elsevier.com/locate/cemconres

Gas permeability and electrical conductivity of structural concretes: Impact of pore structure and pore saturation

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ARTICLE INFO

Article history:
Received 18 February 2016
Received in revised form 23 June 2016
Accepted 15 August 2016
Available online xxxx

Keywords:
Microstructure (B)
Pore size distribution (B)
Permeability (C)
Transport properties (C)
Concrete (E)

ABSTRACT

This paper investigates the gas permeability and the electrical conductivity of structural concretes under different pore saturations. The gas permeability was measured by CemBureau device and the electrical conductivity by alternating current method. The pore structure was characterized by mercury intrusion porosimetry (MIP) and gravimetric methods. The Archie's law is used to interpret the tortuosity of the pore structure. The impact of pore saturation is evaluated through the Van Genuchten-Mualem (VGM) and Kozeny's models. The results show that (1) the global correlation between the gas permeability in dried state and the electrical conductivity in saturated sate is weak; (2) both VGM and Kozeny's models can describe the relative permeability/conductivity, but the VGM model gives more consistent exponents for permeability and conductivity; (3) as the pore gas and liquid phases are both percolated, the gas permeability is correlated to the electrical conductivity for arbitrary pore saturation.

1. Introduction

The durability properties of structural concrete have been valued in the design and construction of civil engineering infrastructures [1]. Since most durability processes in concrete are related to gas and/or liquid transport, the gas permeability and the electrical conductivity are two fundamental quantities: the gas permeability depicts the transport rate of gas phase in concrete pores [2] while the electrical conductivity reflects the percolation and connectivity of liquid phase in pores as the conductivity of solid phases is neglected [3]. In addition, the electrical conductivity of concrete determines the electrical current intensity thus the corrosion rate of reinforced steel in concrete [4]. Actually, the gas permeability and electrical conductivity bear double senses for durability: as the pores are totally occupied by gas/liquid phase, these two quantities belong to the intrinsic properties of concrete materials; as the pores are partially occupied by gas/liquid phase, these two quantities refer to the performance indicators of durability under a given condition for pore saturation.

Compared to conventional infiltrating liquids like water, gas and electrical current can reach much finer pores in concrete. Thus, the gas permeability and electrical conductivity are more adapted to characterize modern concretes with high compactness [5]. The gas permeability has been studied extensively for cement-based materials. The available test methods include steady flow [6,7] or transient flow methods [8,9]. Normally the in-situ measurements show higher dispersion than the laboratory ones due to less homogeneous concrete and larger variation of concrete water content [10]. In literature, the intrinsic gas permeability was measured as 10^{-18} m^2–10^{-16} m^2 for cement-based materials in dried states, and it was observed to correlate linearly to the product of porosity and the square of pore characteristic length of cement pastes and mortars [11–13]. Several authors used CemBureau device to study the impact of pore saturation on the gas permeability of concrete with the difference between low and high saturations approaching 2–3 orders of magnitude [14–16]. The electrical conductivity is favored in recent years due to its low laboratory labor, good measurement stability and nondestructive nature [17,18]. The electrical conductivity of concretes as porous media depends, if the conductivity of solid phases is neglected, on the volume fraction, connectivity and the intrinsic conductivity of pore solution [19], as well as the surface conduction of liquid-solid interface on pores [3]. The available test methods include both surface measurement [20] and pass-through measurement [21]. The electrical conductivity was measured as 1.12×10^{-3}–1.02×10^{-2} S/m for concretes with w/c ratio between 0.3 and 0.55 [22] using Wenner method, and 0.6–14.4 $\times 10^{-3}$ S/m for mortar with w/c = 0.55 using impedance devices [23]. Literature showed that a strong correlation exists for the results from different devices if proper correction factors were taken into account [23,24]. The electrical conductivity of concrete is regarded to relate closely to the pore structure, and the conductivity ratio between concrete and pore solution is linked to porosity and pore tortuosity by Archie's law [25], or porosity and pore connectivity through composite theory [3]. Also, the electrical conductivity was observed to be rather sensitive to the pore saturation, and

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http://dx.doi.org/10.1016/j.cemconres.2016.08.009

the electrical conductivity of mortar (w/c = 0.42) was observed to reduce by 50% as pore saturation ranges from 100% to 85% [23], and the saturation dependence of conductivity was described by a power law with exponents of 3.5–5.0 for cement pastes mortars [19,23].

Making the gas permeability and electrical conductivity useful durability properties for quantitative specification is still in course [26]. To this aim, two issues have to be addressed: how the microstructure and/or composition of concretes influence the properties and how the properties change with the pore saturation. The former can help the material engineers to design structural concretes according to specified properties while the latter is crucial to evaluate the durability performance of structural concretes in service conditions. So far, the knowledge accumulated on these two properties has not fully answered these two questions. This study attempts to address these issues by establishing a comprehensive database of gas permeability and electrical conductivity for typical structural concretes. The pore structure of these concretes is first characterized, and the two properties are measured for different levels of pore saturations. Then, the impact of pore structure and pore saturation is analyzed for the two properties, and the correlation between the gas permeability and electrical conductivity under unsaturated states is explored further. Accordingly, this paper is organized as follows: Section 2 describes the concrete materials and the experimental procedures, detailing the specimens preparation for different pore saturations; Section 3 reports the pore structure characterization of structural concretes; Section 4 addresses the gas permeability and electrical conductivity in terms of pore structure and pore saturation; the correlation between gas permeability and electrical conductivity is deepened in Section 5; the concluding remarks are given in the end.

2. Materials and experiments

2.1. Materials and specimens

Three binders were used in this study: ordinary Portland cement (OPC), OPC incorporating 30% fly ash (OPC-FA), and OPC incorporating 50% slag (OPC-SG). For each binder, four w/b ratios were adopted to prepare concrete materials: 0.3, 0.4, 0.5 and 0.6. Thus, this study covers a total of 12 concretes. In the concrete proportioning, the volumetric ratio between cement paste and aggregates is held constant at 0.35:0.65, with the detailed proportioning in Table 1.

The concrete mixtures were poured into 100 mm cubic molds and cylinder molds with diameter of 150 mm and height of 200 mm, demolded at the age of 1–3 d and then immersed and cured in water at 20 ± 2 °C. The OPC concrete specimens were cured to 90 d while the OPC-FA/SG specimens were cured to 180 d. After these ages, the hydration of OPC, OPC-FA/SG specimens is considered to be stabilized. Afterwards, the specimens were tested for compressive strength, pore structure characterization, gas permeability and electrical conductivity. The specimens and their preparation procedures are summarized in Table 2. The compressive strength was measured on 100 mm cubes and converted to 150 mm cubic strength in the table.

2.2. Pore structure characterization

The pore structure of concrete was detected by MIP and gravimetric methods. For MIP measurements, the cubic specimens of concretes were crushed after curing ages, 90 d for OPC and 180 d for OPC-FA/SG, three samples were prepared for each concrete, and each sample contained particles of 3–5 g. Then these samples were oven-dried under 60 °C to constant weight, i.e. mass change ratio <0.1% during 7 d, before the mercury intrusion. The MIP equipment used in this study is of type Autopore IV 9510 with the intrusion pressure from 1.4 kPa to 414 MPa, corresponding to pore range (diameter) of 800 μm to 3 nm [27]. From the MIP results, both the total porosity and the pore size distribution are available and to be used as common basis for later analysis on the durability properties.

The gravimetric method is to measure the water loss between the saturated and dried specimens, and evaluate the porosity by the volume ratio between water and specimen. For gravimetric measurements, thin slices, 100 mm × 50 mm × 5 mm, were sawed out from the cubic specimens just after water-curing. These slice specimens were vacuum-saturated during 24 h, and the volume of these slices, V_{slice}, was measured following Archimedes principle. Fourteen slice specimens were prepared for each concrete, then seven slices were dried to constant weight under 60 °C and the other seven under 105 °C. Using two drying temperatures intends to make the difference between the capillary porosity and the total porosity occupied by evaporable water. Then the porosity was calculated by the water loss, $\Delta m_{60,105}$, dried under 60 °C or 105 °C, and the volume of these slices,

$$\phi_{60,105} = \frac{\Delta m_{60,105}}{\rho_w V_{slice}} \quad (1)$$

Note that the water loss and the volume refer to the addition quantity of the seven slices to minimize the measurement error due to the heterogeneity of concrete slices.

2.3. Gas permeability

The gas permeability was measured through CemBureau device [7], the device used in this study was detailed in forgoing publications [28, 29] and the infiltrating gas is nitrogen. The principle of CemBureau device is to impose constant pressure gradient, measure the gas flow rate in steady state, and evaluate the gas permeability, k_A (m^2), through extended Darcy's law for compressible fluids [30]. The intrinsic

Table 1
Concrete proportioning for gas permeability and electrical conductivity.

Concrete	w/b (−)	Cement (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	Quartz sand 0–5 mm (kg/m^3)	Crushed coarse aggregate 5–20 mm (kg/m^3)	Compressive strength at 90 d (OPC)/ 180 d(OPC-FA/SG) (MPa)
OPC-3	0.3	563	169	0	0	689	1033	82.1
OPC-4	0.4	485	194	0	0	689	1033	70.8
OPC-5	0.5	426	213	0	0	689	1033	63.5
OPC-6	0.6	380	228	0	0	689	1033	52.6
OPC-FA-3	0.3	394	169	169	0	689	1033	91.9
OPC-FA-4	0.4	340	194	146	0	689	1033	75.9
OPC-FA-5	0.5	298	213	128	0	689	1033	57.8
OPC-FA-6	0.6	266	228	114	0	689	1033	46.8
OPC-SG-3	0.3	282	169	0	282	689	1033	93.5
OPC-SG-4	0.4	243	194	0	243	689	1033	71.7
OPC-SG-5	0.5	213	213	0	213	689	1033	62.4
OPC-SG-6	0.6	190	228	0	190	689	1033	54.8