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Effect of pore structures on gas permeability and chloride diffusivity of concrete

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HIGHLIGHTS

- Permeability, diffusivity and microstructure of concrete with different W/B ratios and admixtures were studied.
- An indicator of contributive porosity was proposed.
- Relationships among permeability, diffusivity, porosity and pore-size distribution were established.
- Correlation of permeability and contributive porosity was obtained.

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ABSTRACT

10 concrete specimens with different water-binder ratios and admixtures were manufactured to analyze the relationship between permeability and microstructure of the test concrete. The gas permeability coefficient and effective chloride diffusion coefficient of concrete were measured by Cembureau method and ASTM C1202 test respectively. In addition, the pore structure of concrete was determined by mercury intrusion porosimetry (MIP) and nuclear magnetic resonance (NMR) respectively. Results show that water-binder ratio and admixture have negligible effect on the distribution of pore size below 10 nm. Besides, the addition of admixtures can decrease the porosity of concrete effectively, except basalt fiber. Moreover, there is an obvious correlation between gas permeability (chloride diffusivity) and porosity of the test concrete. A higher proportion of pore within range of 1–100 nm can be obtained by NMR than that by MIP. The results are opposite when the pore size is >100 nm. There is a good correlation between gas permeability coefficients and contributive porosity with pore diameter of 10–1000 nm, meanwhile, chloride diffusivity is well dependent on contributive porosity with pore diameter of 100–1000 nm. The addition of admixtures will change the relationships between two global permeability coefficients and microstructure parameters of concrete.

1. Introduction

Reinforced concrete (RC) structures are widely used in housing and infrastructure constructions. Their durability in chloride environment has gained considerable attentions [1–3], including microstructure and morphology of concrete [4,5]. Chloride-induced corrosion of steel in RC structures is one of the major deterioration causes [6,7], mainly due to corrosive medium entering into concrete through some transmission channels such as pores and micro cracks. However, the quantitative relations between pores and micro cracks with the durability of concrete structure have not yet been established [8]. Therefore, the permeability of concrete can be used as an important indicator to evaluate durability of concrete structure. As a heterogeneous material, porous characteristic of concrete leads to the permeability of concrete [9], which is related to its pore structure, porosity, strength, curing condition and service environment [5,10,11]. Therefore, the microstructure of concrete and its influence on the macro properties of concrete have been a hotspot of durability research [12–14].

With the development and application of microstructure testing technologies, relevant research on the effect of pore structures and distribution on the permeability of concrete have been carried out [10,14,15]. Generally, pores can be classified into four levels based on pore diameter (d): gel pores ($d < 10$ nm), medium capillary pores (10 nm < d < 100 nm), large capillary pores (100 nm < d < 1000 nm) and air voids ($d > 1000$ nm) [16–18]. The

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influence of pore size on the permeability of concrete is significant, pores >100 nm can obviously increase permeability of concrete [10,17]. Therefore, research on the relationship between porosity and permeability of concrete have been gradually in the spotlight [19,20]. Lafhaj et al. [21] measured the porosity and gas permeability of completely dry and partially saturated mortar samples and suggested that the dependence of permeability on porosity and water content was very significant. Sinsiri et al. [22] found that air permeability of blended cement pastes decreased with porosity. However, Kondraivendhan and Das [23] insisted that it was imprudent to point out that porosity was the sole influencing factor of permeability, since pore size distribution would also have an important and even decisive influence on permeability. Zhang and Li [24] investigated the relationship between effective chloride diffusion coefficient and pore structure of concrete by mercury intrusion porosimetry (MIP) and the Nernst–Einstein–Lu (NEL) method, and confirmed that the permeability of concrete was related to its porosity, however, the correlation coefficient was less than that of pore size distribution, indicating that the resistance to chloride penetration of concrete was strongly influenced by pore size distribution. Neithalath et al. [25] dealt with the extraction of pertinent pore structure features of several pervious concrete mixtures proportioned using different aggregate sizes and their blends. The need to use other pore structure features instead of porosity alone in permeability predictions was emphasized [25]. The conclusions of existing research have shown that the pore structure and distribution are closely related to permeability.

At present, MIP is widely used to investigate pore structure of cement-based materials [26–28]. However, the specimens for MIP method are so small that it's difficult to reflect the real permeability of concrete interface and its mechanism in some cases [29]. Recently, the nuclear magnetic resonance (NMR) technology has been used as an effective method to characterize the microstructure of concrete. NMR method is non-destructive and non-invasive, so the test results are much closer to the reality [29].

In this paper, the gas permeability coefficient and effective chloride diffusion coefficient of concrete were measured by the Cembureau method and ASTM C1202 test respectively. Based on the test results, the relationship between these two coefficients mentioned above was analyzed, and the effects of water-binder ratio and admixtures was examined. In the meantime, microstructures and parameters of concrete such as porosities and pore size distribution were tested by MIP and NMR, and differences of measured results by MIP and NMR were also studied. At last, the influences of water-binder ratio and admixture on the microstructure parameters of concrete and its macro permeability were discussed.

2. Raw materials and mix proportion of test concrete

2.1. Raw materials

In this study, common river sand is used as fine aggregates with fineness modulus of 2.4 and apparent density of 2600 kg/m^3. The maximum size of coarse aggregates is 20 mm with apparent density of 2700 kg/m^3. Besides, Qian-Chao complex Portland cement (P.C. 32.5) is used. The admixtures used in the test include fly ash (FA), silica fume (SF), basalt fiber (BF) and slag (SG). The filament diameter of BF is 17–20 μm and the length is 10–20 mm, in addition, the tensile strength is 2800–3800 MPa and the elastic modulus is 100–110 GPa. Table 1 shows the chemical components of cement, FA, SF and SG.

Fig. 1 shows the Scanning Electron Microscope (SEM) images of cement and admixtures.

2.2. Mix proportion of concrete

To eliminate the influence of raw material randomness on the experiment results, the ratio of fine to coarse aggregates used in the mixes is purposely kept as 32%. The details of the mixture proportions of concrete are summarized in Table 2, in which the percentage of admixture represents the weight percentage of the admixture in the binder.

3. Experimental processes and methods

3.1. Preparation of specimens

For each mix proportion mentioned in Table 2, two rectangular concrete specimens were prepared with the size of 150 mm × 150 mm × 550 mm. Besides, six specimens of Φ 100 mm × 50 mm were cast to test the effective chloride diffusion coefficient by ASTM C1202 test after 28 d standard curing.

In addition, three cubic specimens with the size of 150 mm × 150 mm × 150 mm for each mix proportion were manufactured to measure the cubic compressive strength of concrete. In accordance with the Chinese standards of SL-2006, all specimens above were placed into concrete standard compartments for curing for a period of 28 days with the temperature of 20 ± 5 °C and relative humidity of 95%. The test results of cubic compressive strength are given in Table 2.

3.2. Test methods for gas permeability and effective chloride diffusion coefficient

3.2.1. Specimens for gas permeability of concrete

Three specimens with the size of 150 mm × 150 mm × 50 mm were cut from each rectangular specimen of the same specification for gas permeability test to reduce the influence of material randomness on the experimental results. Fig. 2 shows the concrete specimens and cutting schematic diagram of the samples for gas permeability test.

3.2.2. Test method for gas permeability of concrete

Fig. 3 shows the self-designed device to measure gas permeability coefficient of concrete. It can be used to simultaneously determine gas permeability coefficients of several concrete specimens and reduce the test errors.

Before the gas permeability test, the samples were placed into the YF101-2A blast air oven and dried at 105 ± 5 °C for 48 h, and then cooled to ambient temperature. The Cembureau method recommended by RILEM [30,31] was adopted to measure gas permeability of concrete. Nitrogen with purity 99.99% was used as infiltrating gas. Linking one side of the test sample to air and imposing constant pressure of 0.3 MPa on the other side. The gas

Table 1
Chemical components of materials (wt%).

Designation	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	TiO_2
Cement	24.55	10.48	2.16	51.16	6.01	2.78	–	–
FA	47.66	20.81	9.84	11.51	1.51	–	1.65	–
SG	36.38	17.60	0.889	28.18	14.19	–	–	0.74
SF	98.02	0.416	0.088	0.289	0.414	0.31	–	–