Research Article

Permeability of Concrete and Correlation with Microstructure Parameters Determined by ^1H NMR

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Water and gas permeability coefficients of concrete with different water-binder (w/b) ratios and admixtures were measured by a self-designed test device based on the steady-state flow method for liquid and the method of differential pressure in stability for gas, respectively. In addition, the micropore structure of concrete was determined by ^1H nuclear magnetic resonance (NMR). Results indicated that there are good correlations between water and gas permeability of concrete with different w/b ratios, with correlation coefficient greater than 0.90. Better correlations between water permeability and segmental contributive porosity ranged from 10 to 100 nm and 100 to 1000 nm can be identified, but the gas permeability is more relevant to the segmental contributive porosity ranging from 100 to 1000 nm. Moreover, the correlation between water permeability and contributive porosity for each pore diameter is always better than that of gas permeability. The influence of admixtures on the relationship between permeability and pore size distribution of concrete is significant. Moreover, water permeability coefficient is one or two orders of magnitude lower than the gas permeability coefficient.

1. Introduction

Water and gas permeability are considered reliable indicators to evaluate the durability of concrete [1]. For most liquids, the flow rate is proportional to the pressure gradient and independent of the fluid used. Unlike water permeability, gas permeability is dependent on the nature of gas and shows a linear function of the reciprocal mean pressure, which can be called Klinkenberg effect or the theory of gas slippage [2]. Since water contains gas and liquid states, the water permeability in concrete should include the contributions of these two states mentioned above [3]. For concrete with low porosity and high compactness, it is inappropriate to test water permeability of concrete by the water pressure method [4, 5]. Anez et al. proposed an approximated linear relationship between gas permeability, water permeability, reciprocal mean pressure, and Klinkenberg factor [6]. Previous research indicated that water permeability coefficient was 1~2 orders of magnitude lower

than gas permeability coefficient [7]. Kameche et al. [8] suggested that the significant difference between water and gas permeability coefficients of concrete may be attributed to different pretreatment methods of specimens. Skoczylas and Henry [9] found that when pure water is injected into the pores of concrete, the chemical equilibrium of various phases presented in concrete will be disrupted, leading to a dissolution or precipitation phenomena of micro-components in concrete. Marchand [10] indicated that the effective pore diameter is progressively reduced with water penetration into sample due to the expansion of cement-based materials caused by the capillary adsorption of water. It is worth noting that, to determine the water permeability coefficient of concrete, an accurate and reproducible measurement becomes tedious and difficult [11], and the internal water saturation will have a greater impact on the test results [12]. Therefore, the focus has been shifted to gas permeability, which is easier to measure, requires less time, and produces more reproducible results [13]. If an effective

mutual relationship between water and gas permeability of concrete can be determined, a rapid and easy estimation on water permeability coefficient can be obtained.

It is well known that there is a good correlation between the microstructure parameters of concrete and its permeability [14]. Chen et al. [15] used limestone powder as a cement substitute to evaluate the water resistance of concrete and found a significant linear correlation between permeable porosity and water penetration depth, as well as sorptivity coefficient. Yan et al. [16] investigated the relationship between transfer properties and porosity of a normalized mortar heated up to 600°C. Sinsiri et al. [17] indicated that gas permeability of cement-based materials with fly ash decreased with porosity. By investigating the effects of clinker and limestone quality on gas permeability, water absorption, and pore structure, Tsivilis et al. [18] ascertained that the pore size distribution, especially the mean pore size, affects the gas permeability and water absorption of concrete. At present, numerous techniques have been employed to investigate the microstructure of concrete, including nitrogen adsorption, gravimetry, X-ray computed tomography (X-CT), mercury intrusion porosimetry (MIP), and ^1H nuclear magnetic resonance (NMR). The sample size of the MIP test is small, which is difficult to reflect the real situation of concrete. In addition, the high-pressure intrusion by mercury and pore shielding effect may either deform or destroy the sample, leading to inaccurate results [19]. NMR is one of the most effective probes to obtain the microstructure parameters closer to the real situation, with the noninvasive and nondestructive properties. Ji et al. [20] evidenced that the peaks of transverse relaxation time distribution correlate with the microstructure of fresh cement paste based on ^1H low-field NMR. Zhang et al. [21] measured pore characteristic parameters and pore-size distribution with exposure time by NMR technology. Tziotziou et al. [22] applied ^1H nuclear magnetic resonance relaxation to monitor the hydration and porosity evolution of lime-pozzolan mixtures during its setting in real time. Zhou et al. [23] investigated the pore structure of white cement mortars during water vapor adsorption kinetics by the NMR technique. Thus, it can be seen that the NMR method has been increasingly used to characterize the microstructure parameters of concrete in recent years. However, research on the relationship between water as well as gas permeability and porosity measured by NMR is still rare.

To investigate the correlation between water and gas permeability of concrete, test concrete mixture proportions with different water-binder (w/b) ratios and mixtures were designed. Firstly, water and gas permeability coefficients of the test concrete were measured with a self-designed test device based on the method of differential pressure in stability for gas [24] and the steady-state flow method for liquid. The microstructure parameters such as porosity and pore size distribution of the test concrete were tested by NMR. Secondly, based on the test results, the influences of w/b ratio and admixtures on water and gas permeability of concrete were explored. Moreover, the correlation between water and gas permeability was analyzed. Further, the reasons and influence factors causing a difference between

water and gas permeability coefficients were attempted to be identified, and the influences of w/b ratio and admixture on the microstructure parameters of concrete and its macro-permeability were discussed. At last, the degree of correlation between water and gas permeability and segmental contributive porosity with different pore diameters was analyzed.

2. Materials and Proportions of Concrete

River sand with an apparent density of 2600 kg/m^3 and modulus of fineness of 2.5 were used as fine aggregate. Coarse aggregate with an apparent density of 2700 kg/m^3 was gravel with a maximum particle size of 40 mm and a continuous grading range of 5–40 mm. The weight of tap water for mixing was 190 kg/m^3 . Portland cement P.C 32.5 was used, with detailed properties shown in Table 1.

Since fly ash (FA) and silica fume (SF) are the widely used admixtures, and basalt fiber (BF) is gaining extensive attentions recently, therefore, these three types of admixture are chosen to investigate their effect on the permeability and microstructural properties of concrete. The chemical compositions of used cement and admixtures are listed in Table 2.

Nine concrete mixtures (Table 3) were designed to investigate the influences of w/b ratio and admixture on water and gas permeability of concrete.

3. Experimental Procedure and Methods

3.1. Specimens Casting. According to the concrete mixtures mentioned in Table 3, for each mix proportion, two rectangular concrete specimens ($150\text{ mm} \times 150\text{ mm} \times 550\text{ mm}$) were produced. All specimens were cured in accordance with test code for hydraulic concrete (SL352-2006). After 28 days of curing, each rectangular specimen was cut into six pieces with size of $150\text{ mm} \times 150\text{ mm} \times 50\text{ mm}$. Three were used to measure water permeability and the other three were used to measure gas permeability. Figure 1 shows the schematic diagram of cutting concrete samples.

In addition, for each mix proportion, three cubic specimens with side length of 150 mm were cast simultaneously and cured in the standard curing room. Then, the 28 d compressive strength of cubic concrete specimens was measured, as shown in Table 3.

3.2. Test Method for Permeability. It is well known that, for concrete with lower porosity, its pore size is in a micrometer or nanometer scale. Moreover, the pores with higher tortuosity and lower connectivity may lead to lower water and gas permeability of concrete. In general, the water permeability of concrete ranges from 10^{-19} m^2 to 10^{-17} m^2 , while the gas permeability is higher than that of water permeability at least one or two orders of magnitude [7, 8].

It is time-consuming to infiltrate water or gas from one side of cement-based specimen to the other side, since the seepage flow is very small. Moreover, it is difficult to accurately measure the seepage flow volume in a unit time. Therefore, an experimental device which can measure water

TABLE 1: Physical and mechanical properties of cement.

Standard consistency (%)	Fineness (%)	Density (g/m ³)	Setting time (min)		Flexural strength (MPa)		Compressive strength (MPa)		Stability
29.0	5.6	3.02	Initial setting 250	Final setting 320	3 d 4.12	28 d 5.68	3 d 20.4	28 d 51.3	Qualification

TABLE 2: Chemical compositions of cement and mineral admixtures (%).

Material	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO
Cement	24.55	10.48	2.16	51.16	6.01
Fly ash	47.66	20.81	9.84	11.51	1.51
Silica fume	98.02	0.42	0.09	0.29	0.41
Basalt fiber	54.00	16.50	11.50	7.00	4.50

TABLE 3: Concrete mixture proportions^f.

Number	Content (kg/m ³)				Aggregate ^e		W/B	28 d compressive strength (MPa)
	C	FA	SF	BF	F	C		
A1	475.0	—	—	—	552	1174	0.40	35.4
A2	422.0	—	—	—	567	1204	0.45	29.0
A3	380.0	—	—	—	578	1229	0.50	25.7
A4	346.0	—	—	—	589	1249	0.55	21.9
A5	317.0	—	—	—	597	1269	0.60	16.9
A6 ^a	304.0	76	—	—	578	1229	0.50	22.2
A7 ^b	266.0	114	—	—	578	1229	0.50	21.2
A8 ^c	361.0	—	19	—	578	1229	0.50	31.0
A9 ^d	380.0	—	—	1.03	578	1229	0.50	29.3

^aA6: cement replacement FA, 20% by weight of 380 kg cement. ^bA7: cement replacement FA, 30% by weight of 380 kg cement. ^cA8: cement replacement SF, 5% by weight of 380 kg cement. ^dA9: 0.3% by volume of cement, which is 1.03 kg/m³. ^eFine aggregates (F): 100% m/m passing an 8 mm sieve, 96.5% m/m passing a 4 mm sieve. Coarse aggregates (C): 100% m/m passing a 40 mm sieve, 40% m/m passing a 16 mm sieve. ^fA1–A7 in Table 3 is identical to the content in Table 2 of [24], A8 and A9 herein refer to A9 and A10 in Table 2 of [24].

FIGURE 1: Schematic cutting on concrete samples.

and gas permeability coefficients of specimens and reduce test errors was designed in this paper, based on the method of differential pressure in stability for gas [25, 26] and the

steady-state flow method for liquid [2]. By comparing the experimental measurements with results from other literature, the self-designed device has a relatively simple test method and much higher stability of test results. Figures 2 and 3 show the schematic diagram of the self-designed device and principle for testing permeability of concrete.

To measure water permeability coefficient, the specimens should be put into distilled water for 24 hours under vacuum. Moreover, the specimens were laterally sealed by wax to ensure unidirectional flow of water and avoid side leakage during the permeability test. And then, they were put into the device, located between top cap and clamp plate, as shown in Figure 3, to ensure a square water permeable area of 0.0064 m² with side of 80 mm, square rubber rings of 5 mm thickness, 80 mm inside length, and 135 mm outside length was placed on upper and lower faces of the specimens. At last, a pressure was applied to the specimen by the H4-S fully automatic permeameter to accelerate the water flow. The pressure increased from 0 MPa to 2 MPa and remained unchanged for 8 hours. Until reaching a stable flow of water, the water flux was measured every four hours. After seepage of water has stabilized, the water quantity flowing through

FIGURE 2: Schematic diagram of device for measuring permeability of concrete.

FIGURE 3: Principle for testing permeability of concrete.

concrete specimen was measured by reading the increase of water level in a pipette. The steady-state flow Q was obtained by the average of three recordings after a stable flow. Boundary conditions of water permeability in concrete are shown in Figure 4.

In a steady injection state, the pressure variation in the sample is given by the well-known expression [27]:

$$P(x) = \sqrt{P_i^2 \left(1 - \frac{x}{h}\right) + P_0^2 \frac{x}{h}}, \quad (1)$$

where P_i is the injection pressure (MPa), P_0 is the draining pressure (MPa), which is maintained at atmospheric level in this case, and h is the length of the specimen (m).

According to the boundary conditions in Figure 4, Darcy's law can be written for a one-dimensional flow [27–29], as shown in

$$V_x = -\frac{K_x}{\mu} \frac{dP}{dx}, \quad (2)$$

FIGURE 4: Boundary conditions.

where V_x is the water or gas velocity (m/s) and μ is the viscosity (Pa·s).

Substituting the boundary condition of water penetration test into equation (2) and the equation for water permeability coefficient can be obtained:

$$K_w = \mu_w \frac{Q}{\Delta P} \frac{h}{A}, \quad (3)$$

where μ_w is the dynamic viscosity of water (depending on the temperature of water in the experiment) (10^{-6} kPa · s), Q is the average flow through the concrete (m^3/s), h is the height of the specimen (m), A is the cross-sectional area of water (m^2), and ΔP is the difference value of water pressure between upper and lower surfaces of test samples (MPa).

The procedure of gas permeability test followed the Cembureau method recommended by RILEM, in which N_2 of high purity was used as the injection [25, 26]. As the permeability test is based on the measurement of intrinsic permeability by gas injection, the sample must be dried continuously for 48 h in an oven, drying at a temperature of $105^\circ\text{C} \pm 5^\circ\text{C}$ before testing. Then, the samples were weighted when they were cooled to room temperature. The upper surface of the specimen for gas permeability was connected to the atmosphere and the lower surface was subjected to a constant upstream pressure of 0.3 MPa (injection pressure). The volumetric flow rate of the gas was measured when the injection was continued for 30 minutes to ensure that the gas flew stably through the specimen (steady state).

Unlike water, gas is compressible. Therefore, it is necessary to correct the gas permeability coefficient K_g based on equation (4), which can be expressed as follows [8, 30]:

$$K_g = \frac{h}{A} \mu_g \frac{2QP_a}{(P^2 - P_a^2)}, \quad (4)$$

where μ_g is the dynamic viscosity of N_2 (depending on the temperature of N_2 in the experiment) (kPa · s), Q is the volumetric flow (m^3/s), h is the height of the specimen (m), A is the cross-sectional area of gas (m^2), P is the injection pressure (MPa), and P_a is the atmospheric pressure (MPa).

3.3. NMR to Determine Microscopic Structure of Concrete. MesoMR23-060H-I, produced by Niumag Electric Corporation, Suzhou City, Jiangsu Province, China, was adopted for the ^1H NMR test. In this experiment, the NMR test instrument has a 0.5 T constant magnetic field and a radio-frequency coil of 60 mm in diameter and is operating at 23.4033 MHz and 32°C magnet temperature. Table 4 shows the Carr Purcell Meiboom Gill (CPMG) parameters of transverse relaxation time (T_2) test.

The cubic samples with side length of 40 mm were used for the NMR test, which were cut down from the rectangular concrete specimens. The specific test steps are as follows.

- (1) The dust on the surface of the samples was cleaned with a brush
- (2) The samples were immersed into distilled water at the vacuum pressure of 0.1 MPa for 10 hours to ensure that the samples were fully water saturated [31]
- (3) The specimens were taken out of the water and the exterior moisture was wiped off and then the specimens were wrapped with preservative films
- (4) The specimens were placed in the magnet coil to perform the ^1H NMR test

Temperature and magnetic field intensity may have effects on the test results. Therefore, after determining the

CPMG parameters, the relationship between the unit volume nuclear magnetic signal and porosity was standardized based on the standard sample with a predetermined porosity. Then, the same parameters and test steps were used to calibrate the standard sample and obtain the calibration curve. Figure 5 shows the calibration curve.

Based on the hypothesis of fast exchange, when the sample is filled with water, the ratio of the T_2 value of a single pore to surface-to-volume ratio is well proportional. Thus, the pore distribution can be determined based on the T_2 spectrum as follows [32, 33]:

$$\frac{1}{T_2} \approx \frac{1}{T_{2,\text{sur}}} = \rho_2 \times \left(\frac{A}{V} \right), \quad (5)$$

where T_2 is the relaxation time of water in pore, $T_{2,\text{sur}}$ is the relaxation time of surface, T_2 is the surface relativity, A is the area of the pore wall, and V is the fluid volume.

4. Results and Analysis

4.1. Permeability and Its Influencing Factors. Water and gas permeability coefficient of concrete with different water-binder ratios and admixtures at the age of 28 d are shown in Figure 6. It is worth noting that the values of water and gas permeability coefficients are the average value after eliminating abnormal numbers with the Grubbs method [34].

For concrete without admixtures (A1–A5), both increasing water and gas permeability coefficients with w/b ratio can be observed in Figure 6, suggesting that w/b ratio has a strong influence on water and gas permeability. Moreover, to investigate the effect of admixture on permeability, concretes A6–A9 were used to compare with A3. It can be observed that adding admixtures into concrete (except A9, concrete with basalt fiber), the permeability can be reduced obviously. Among them, silica fume (A8) has the most significant reduction effect, which is similar to the conclusions of Ismail et al. [35] and Badogiannis et al. [36]. The decreasing effect of admixtures on these three permeability coefficients in descending order is $A8 > A7 > A6$. The reasons for the effect of admixtures on permeability can be attributed to the following. First, the incorporation of fibers into concrete increases micro-cracks, leading to the increased water and gas permeability coefficients, when compared with ordinary concrete. Second, the secondary hydration of concrete with silica fume can be completed in a relatively short time, which is more rapid than fly ash concrete; that is, fly ash concrete is still premature at the age of 28 d. Therefore, the effect of silica fume on reducing the permeability coefficient is more obvious than that of fly ash.

In addition, the change effects of admixture on water and gas permeability coefficient are different, as shown in Table 5. In Table 5, minus and plus represents a decrease and increase when compared with A3, respectively.

As shown in Table 5, for the same admixture, the effect of admixture on water permeability coefficient is the most significant. Taking A6 for example, the relative reduction rate of permeability coefficient is K_w (15.3%) $>$ K_g (9.0%) $>$ D (2.2%). A similar trend can be found in concrete with other

TABLE 4: CPMG parameters used in test.

Parameters	Sf (MHz)	O1 (Hz)	P1 (μ s)	P2 (μ s)	SW (kHz)	TW (ms)	RG1 (db)	DRG1	PRG	NS	TE (ms)	NECH
Value	23	403330	13	26	250	3000	10	3	1	64	0.2	16000

FIGURE 5: Calibration curve of NMR.

FIGURE 6: Water and gas permeability coefficient of concrete (28 d).

TABLE 5: Change rates of permeability when comparing A3 with concrete with admixtures.

Number	Change rate of K_w (%)	Change rate of K_g (%)
A6	-15.3	-9.0
A7	-22.0	-17.3
A8	-10.5	-6.2
A9	-35.9	-17.4
A10	+26.0	+24.3

admixtures. Therefore, it can be concluded that different pore structures are formed when adding different admixtures in concrete, resulting in the different permeability.

4.2. Correlation between Water (Gas) Permeability and Microstructure Parameters. Generally, concrete with good chloride impermeability has superior water and gas impermeability. However, since the mechanisms of water and gas permeability are different, depending on the microstructure of concrete [37, 38], it is necessary to explore the correlation between water and gas permeability [9, 39]. The correlation between water and gas permeability is shown in Figure 7. It can be found from Figure 7 that gas and water permeability coefficient both increase proportionally with w/b ratio. A good correlation between water and gas permeability, with R^2 of 0.918, can be obtained.

Table 6 shows the porosity of the test concrete measured by NMR [24].

FIGURE 7: Water permeability coefficient versus gas permeability coefficient of concrete.

TABLE 6: Porosity of test concrete (%).

A1	A2	A3	A4	A5	A6	A7	A8	A9
9.36	9.54	9.97	13.05	15.46	9.45	9.10	8.73	14.72

Previous research has indicated that, according to the pore diameter (d), pores can be classified into gel pores (<10 nm), medium capillary pores (10–100 nm), large capillary pores (100–1000 nm), and air voids (>1000 nm) [40, 41]. The pore size distribution of the test concrete measured by the NMR method is described in [24].

Actually, even with the same porosity, different pore size distributions may lead to different permeability. In addition, the size of media also has an influence on the transfer property in concrete. Thus, it is essential to consider the effects of pore size and porosity simultaneously on permeability. Zhang et al. [21] has defined an indicator-contributive porosity, that is, multiplying the porosity by the related pore size percentage in total porosity, which reflects the proportion of pore volume in a certain pore size range to the total volume of sample, to describe the combined effects of pore size and porosity on water and gas permeability. Figure 8 shows the contributive porosity within different ranges of pore size in concrete.

From Figure 8, it can be seen that the contributive porosity of large pore (100–1000 nm) increases with w/b ratio, leading to an increasing permeability. In addition, except basalt fiber (A9), adding admixtures into concrete can reduce porosity and contributive porosity of large pore significantly, making concrete more impermeable. Then, according to the contributive porosity determined in Figure 8 and the permeability given in Figure 6, the correlation between contributive porosity within different ranges of pore size and permeability as well as diffusivity can be determined. Table 7 shows the corresponding correlation coefficients R^2 .

From Table 7, it can be seen that the correlation between water permeability and contributive porosity for each pore diameter is always better than that of gas permeability,

whether admixtures are adding or not. This may be attributed to the Klinkenberg effect. When the pore size is compared to the mean free path of the gas molecules, the gas flow at the pore walls will have a slip effect, which increases the gas flow rate. Eventually, the gas permeability is larger than the intrinsic (water) permeability [6]. Besides, better correlations between water permeability and segmental contributive porosity ranging from 10 to 100 nm and 100 to 1000 nm can be observed, but the gas permeability is more relevant to the segmental contributive porosity ranged from 100–1000 nm. It is known that N_2 has a smaller molecule with a dynamic size of 0.364 nm [42], and the diameter of water molecules is 0.22 nm [43]. Thus, N_2 and water molecules can pass through the small capillary pores easily. Moreover, N_2 and water molecules can pass through pores easily when the increasing quantity of pore diameter is 100–1000 nm.

There is a vital influence of admixtures on the relationship between permeability and pore size distribution of concrete [44, 45]. Adding admixtures will cause a change of interface between cement paste and aggregate and the structure and morphology of pores. Part of connected pores may be blocked to be unconnected pores or expanded to be cracks [46, 47]. From Table 7, it can be seen that after adding admixtures, the correlation between contributive porosity of each pore size range with water permeability as well as gas permeability is reduced to a certain degree. This is because after adding admixtures, the porosity of concrete decreased; meanwhile, the pore size distribution of macropores and micropores decreased and increased, respectively.

4.3. Analysis of Differences between Water and Gas Permeability Coefficients. Figure 9 shows the change of the ratio of water and gas permeability coefficients (K_g/K_w) with w/b ratio.

It can be seen that (K_g/K_w) decreases gradually with the increase of w/b ratio. Moreover, the slope tends to be sharp

FIGURE 8: Cumulative contributive porosity within different pore size in concrete.

TABLE 7: R^2 of permeability and contributive porosity within different ranges of pore diameter in concrete.

		<10 nm	10 nm~100 nm	100 nm~1000 nm	>1000 nm
Different water-binder ratios	Water permeability	0.787	0.978	0.999	0.639
	Gas permeability	0.595	0.793	0.901	0.596
Different admixtures	Water permeability	0.913	0.889	0.984	0.837
	Gas permeability	0.882	0.853	0.967	0.827

FIGURE 9: (K_g/K_w) versus water-binder ratio of concrete.

when w/b ratio is higher than 0.50. In addition, admixture also has an influence on (K_g/K_w) . Figure 10 shows the change of (K_g/K_w) with admixtures.

In Figure 10, A8 has the least permeability, and the permeability of A9 is the largest. Thus, it can be observed from Figure 10 that (K_g/K_w) decreases with the increase of

FIGURE 10: (K_g/K_w) of concrete with different admixtures.

permeability. Moreover, the decrease degree of (K_g/K_w) is positively related to permeability. Additionally, it can be observed that water permeability coefficient of concrete with admixtures is one or two orders of magnitude lower than the gas permeability coefficient, which may be related to the Klinkenberg effect [7, 8, 48].

It is found that, in the water permeability test, the time required to reach a steady seepage state is much longer than that in the gas permeability test. Besides, a continuous decrease in the injected water flow rate can be identified when conducting the water permeability test. These phenomena can be attributed to the following main reasons. First, when pure water is injected into pores, the chemical equilibrium of various phases presented in concrete will be disrupted, leading to a dissolution or precipitation phenomena of microcomponents in concrete. The rate of dissolution or precipitation is intrinsically much faster than the transport rate of water [9]. Moreover, the effective diameter of pores is progressively reduced with water penetration in the sample due to the expansion of cement-based materials caused by the capillary adsorption of water [10, 49], which may be a reason causing a smaller water permeability coefficient. This phenomenon is quite similar to the self-healing of cracks under water penetration [50].

5. Conclusions

The conclusions of this work can be summarized as follows:

- (1) There is an obvious effective mutual relationship between water and gas permeability of concrete. Water permeability coefficient is one or two orders of magnitude lower than gas permeability coefficient of the test concrete. The difference between water and gas permeability coefficient increases with the decreasing of concrete permeability. Water and gas permeability coefficient of concrete both increase with w/b ratio, which can be considered as a main factor affecting the impermeability of concrete. The variations of water and gas permeability coefficient of concrete with admixtures are similar, but the effects of the same admixture on water and gas permeability of concrete are different, in which water

permeability coefficient is most dependent on the addition of admixtures.

- (2) Relationship between microstructure and water permeability is different from that and gas permeability. Better correlations between water permeability and segmental contributive porosity ranging from 10 to 100 nm and 100 to 1000 nm can be observed, but the gas permeability is more relevant to the segmental contributive porosity ranging from 100 to 1000 nm. Moreover, the correlation of water permeability with contributive porosity for each pore diameter is always better than that of gas permeability. Besides, the addition of admixtures has a great effect on the relationship between macroscopic permeability and pore size distribution.

Data Availability

The experiment is a series of experiments completed by the author together with Fang Zhaofeng and Bianfan. The data in the manuscript comes from this experiment.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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