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STUDY ON THE CORRELATION BETWEEN SHPC PORE STRUCTURE AND AIR PERMEABILITY

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Original scientific paper
The micro-porous structure of slag high performance concrete (SHPC) imposes great influence on its permeability and durability. Based on air permeability experiment and mercury injection experiment, the author analyses the correlation between SHPC pore structure and air permeability by taking parameters of SHPC air permeability and pore structure as random variables, finding the mechanism and level of influence of various mix proportions of SHPC pore structure parameters on air permeability. Research and analysis show that median pore diameter and threshold diameter of SHPC are certainly correlated to air permeability and can be used to represent SHPC air permeability, while other parameters are not closely correlated to it and cannot represent SHPC air permeability directly by single one.

Keywords: *air permeability; correlation; pore structure; SHPC*

Analiza korelacije između strukture pora SHPC i provodljivosti zraka

Izvorni znanstveni članak
Mikro-porozna struktura betona od troske visokih radnih karakteristika (SHPC - Slag High Performance Concrete) od velikog je utjecaja na njegovu provodljivost i izdržljivost. Na temelju eksperimenta provodljivosti zraka i eksperimenta s ubrizgavanjem žive, autor analizira korelaciju između strukture pora SHPC i provodljivosti zraka, uzimajući parametre provodljivosti zraka i strukture pora SHPC kao slučajne varijable, tražeći mehanizam i stupanj utjecaja različitih omjera miješanja parametara strukture pora SHPC na provodljivost zraka. Istraživanje i analiza pokazuju da su promjer središnje pore i promjer praga SHPC svakako povezani s provodljivosti zraka i mogu se koristiti za predstavljanje zračne provodljivosti SHPC, dok ostali parametri nisu s njom usko povezani i ne mogu je pojedinačno predstavljati.

Ključne riječi: *korelacija; provodljivost zraka; SHPC; struktura pore*

1 Introduction

Permeability and durability of SHPC are closely related to each other, and their low permeability leads to high durability. After becoming hardened, concrete embodies complicated pore structure. Such micro-porous structure imposes great influence on its macroscopic behaviours such as intensity, deformability, thermal conductivity, permeability and durability [1÷3], while permeability can better reflect the change of interconnected pore structure of SHPC. Thus, knowledge about concrete pore structure and its influence mechanism on permeability is a must for study on macroscopic permeability of SHPC. Many scholars take mathematical statistics from mercury injection experiment such as threshold diameter [4], mode pore diameter and mean pore diameter as representative diameters to study their influence on concrete permeability [5÷10]. Sugiyama et al. [11] studied the relation between concrete permeability with different mix proportions and porosity, finding that air permeability increases as porosity increases. However, the research by Abbas et al. [12], Parrott [13] and Tsivilis et al. [14÷16] shows no obvious correlation between the two in that permeability mainly depends on interconnected pore structure. Zhao Tiejun discussed correlation between parameters like pore diameter distribution, threshold diameter, mode pore diameter and mean pore diameter and chloridion permeability of SHPC. He also pointed out that owing to unknown effect diameter of different pore diameters on chloridion permeability, the analysis by pore diameter distribution can only be used for qualitative research [8].

This paper, based on SHPC air permeability experiment and mercury injection experiment, analyses the correlation between SHPC pore structure and air permeability by taking parameters of SHPC air permeability and pore structure as random variables. Meanwhile, this paper, based on the experimental analysis [17÷19], studies the mechanism and level of influence of various mix proportions of SHPC pore structure parameters on air permeability to obtain pore structure parameters representing SHPC air permeability.

2 Experiment

2.1 Raw materials for the experiment

Properties of the raw materials used in the experiment are as follows:

1) Cement: Conch Ordinary Portland Cement Level 42,5.
2) Aggregate: Coarse aggregate is artificial limestone gravel by continuous grading with the maximum nominal size of 20mm and the apparent density of $2,68\times10^{-3}$ kg/m^3. Fine aggregate is natural river sand with fineness modulus of 2,9 and the apparent density of $2,61\times10^{-3}$kg/m^3.
3) Addition: Slag is ordinary fine one provided by Shanghai Construction Group, with its chemical compositions and physical properties shown in Tab. 1 [20].
4) Superplasticizing Admixture: Superplasticizing admixture is M-100 naphthalene series superplasticizer (powder) produced by Shanghai Kao Chemicals Co., Ltd with its Na_2SO_4 content less than 0,4%. The author conducts the experiment for compatibility of M-100 superplasticizer and cement, finding the two are fairly compatible [1].

Table 1 Chemical compositions and physical properties of slag

Chemical compositions and physical properties	Value
CaO (%)	30,13
SiO_2 (%)	36,39
Al_2O_3 (%)	13,76
Fe_2O_3 (%)	2,44
MgO (%)	9,36
SO_3 (%)	1,30
Density (kg/m^3)	2890,00
Specific surface area (m^2/g)	371,00
Fineness of 80μm sieve residue) (%)	0,10
Fineness of 45μm sieve residue) (%)	3,00

2.2 Mix proportions of SHPC

Water-binder ratio, maintenance period, addition and mixing amount have relatively greater effect on SHPC pore structure and air permeability [21÷23]. Based on the experimental requirements, this paper sets water-binder ratio as 0,25, 0,30 and 0,35, slurry gather ratio as 32,3÷35,7% and sand ratio as 40%. To study the general rule of air permeability, the choice of addition amount is not limited, with the maximum amount being at 60%. Thus, mix proportions of some components maybe do not follow those of high performance concrete. The amount of super plasticizing admixture is decided by the actual work of concrete, which is mainly to make the slump bigger than 20 cm with sound workability (segregation and water segregation resistance). Specific mix proportion is shown in Tab. 2 [2].

Table 2 Mix proportions of SHPC

Mix proportions	w/b	Cement (kg)	Addition (%)	Stone (kg)	Sand (kg)	Water (kg)	Super plasticizing admixture dosage (%)
BSC11	0,25	467,5	15	1074	716	137,5	1,8
BSC12	0,25	385	30	1074	716	137,5	1,8
BSC21	0,30	467,5	15	1030	687	165	1,2
BSC22	0,30	385	30	1030	687	165	1,2
BSC23	0,30	302,5	45	1030	687	165	1,2
BSC24	0,30	220	60	1030	687	165	1,2
BSC31	0,35	467,5	15	986	658	192,5	0,6
BSC32	0,35	385	30	986	658	192,5	0,6
BSC33	0,35	302,5	45	986	658	192,5	0,9
BSC34	0,35	220	60	986	658	192,5	0,9

2.3 Experimental method and procedures

2.3.1 Test of air permeability parameters

The test is carried out in the Key Laboratory of Advance Civil Engineering Materials of the Ministry of Education at Tongji University in China. Test-piece is prepared, maintained and pre-processed in line with standard process of Cembureau Method [24] suggested by RILEM. The method is as follows: in the experiment, test-piece is connected to atmosphere on one end, with the other end gas by constant pressure (N_2 of high purity in this experiment). Then after half an hour (which is to ensure gas in the test-piece flows at a constant speed), flow velocity of gas is tested. Finally, K_g, the air permeability parameter of the test-piece under such pressure, is calculated according to Eq. (1).

$$K_g = \frac{Q}{t}\frac{L}{A}\mu\frac{2P_a}{(P^2-P_a^2)} \tag{1}$$

Where:
- K_g is the air permeability parameter of the test-piece with unit of m^2,
- Q/t is the flow velocity of gas as the testing value with the unit of m^3/s,
- P_a is the atmosphere pressure with the unit of N/m^2,
- P is the experimental pressure with the unit of N/m^2,
- L is the thickness of test-piece as the testing value with the unit of m,
- A is the section area as the testing value with the unit of m^2,
- μ is the gas viscosity with the unit of s·N/m^2.

Air permeability parameters of all test pieces with different mix proportions are tested in the same single experiment. Also, they are confirmed in line with the following rule: for each concrete with certain mix proportion, three test pieces are chosen to test air permeability parameters under three different pressures, with the average value being the parameter. Owing to great discreteness of the testing result, in statistics processing, the test piece with relative value different from the other two by over 120% is to be disregarded, and the average value of the other two is to be the air permeability parameter. However, if relative values of the three are different from each other by over 120%, it is perceived that the testing result cannot reflect true rule and the mix proportion is disregarded.

Through experiment, air permeability parameter with the 90-day maintenance period is obtained. Mix proportion that violates truth is not seen in the result analysis.

2.3.2 Test of pore structure parameters

Mercury intrusion porosimetry is used to test pore structure parameters. Mercury intrusion equipment is made by staff in the Lab and pore test is conducted by automatic scan-Model 60 pore size apparatus produced by American Quantachrome Company, with the pore size ranging from 17,78×10$^{−10}$ to 21340×10$^{−10}$ m.

In this experiment, the particle size of coarse aggregate of concrete is bigger than 10mm, as can be seen in the reference [25]. This mercury injection experiment chooses sample in line with the following rule: press to crash test piece of SHPC with 90-day maintenance period by press machine, then choose the concrete rubble with complete inner part to get the experimental sample. The sample with the particle of 5mm excludes coarse aggregate and large-particle sand but includes interface region.

3 Result of SHPC mercury injection experiment and calculation of parameters of pore structure

The direct result of mercury injection experiment is pressure–cumulative pore volume relationship modes or diameter–cumulative pore volume relationship modes, obtaining characteristic parameters of each frequently-used pore structure by further calculation – parameters of mathematical statistics like total porosity V, porosity V_i of graded pore, surface area, and threshold pore diameter, mean pore diameter, median pore diameter and mode pore diameter of characterizing distribution feature of diameters.

The author closely observed the destruction morphology of concrete in the compressive strength experiment [26]. The result reveals that, except several mixture ratios (the amount of mineral admixture is above 45%), the destruction morphology of concrete is the same as the research in the reference [27]: the surface of fracture is flat and penetrates the aggregate. Therefore, in this article, the author approximates the interface region to the hardened paste structure.

The definition of threshold pore diameter: the corresponding diameter when the volume of press-in mercury is increased obviously. The pressure – on the cumulative pore volume curve, the threshold pore diameter corresponds to the end point pressure yielded by the mercury volume; on the pore diameter distribution integral curve, the threshold pore diameter is the intersection point between the tangent line of the mutational point of the slope of curve and the abscissa ln$r$. The physical significance is that the relatively big pores on cellular material are connected by relatively small pores and the threshold pore diameter refers to the pore grade that can connect relatively big pores while pores bigger than this diameter cannot become intercommunicating pores.

The mean pore diameter can be calculated by the following equation [28]:

$$\lg \bar{r} = \frac{\int_{\lg r_0}^{\lg r_e} V d \lg r}{V_{\max}} + \lg r_0 \qquad (2)$$

Where:

- r_0 is the smallest pore diameter measured,
- $V_{\max}$ is the volume of other pores bigger than r_0,
- r_e is the biggest pore diameter when the pore volume is 0 on the pore diameter distribution curve.

Therefore, the pore diameter distribution curve is not function curve and the author turns the above-mentioned equation to:

$$\lg \bar{r} = \frac{\sum_i V_i d \lg r_i}{V_{\max}} + \lg r_0 \qquad (3)$$

The 29th reference defines the mean pore diameter as the corresponding diameter when the volume of press-in mercury is 50% [24], but the result differs greatly from the numerical value calculated from equation (3). The author calculates the parameters of each ratio based on this definition, but defined as median pore diameter.

Plot the slope of pore diameter distribution curve $dV/d\lg r$ to $d\lg r$ and we can get pore diameter distribution differential curve. The pore diameter corresponding to peak value on the differential curve is the mode pore diameter. The physical significance is that this is the pore diameter with the largest occurrence probability [29]. Lu Cui and others [30] think there are two peak values on the hardened paste pore diameter differential curve: the left peak value is bigger than 100×10^{-10} m, corresponding to capillary pore structure; the right peak value is lower than 100×10^{-10} m, corresponding to gel pore structure.

The surface area of pores can be calculated by the following equation:

$$S = \frac{1}{\sigma \cos\theta} \sum_i P_i V_i \qquad (4)$$

Based on the above-mentioned definitions, we can obtain by calculation the total porosity, threshold pore diameter, mean pore diameter, median pore diameter, and mode pore diameter and pore surface area representing the parameter of pore structure of concrete of all ratios.

4 SHPC air permeability and correlation analysis on characteristic parameters of pore structure

4.1 Correlation between air permeability and total porosity

The author draws the scatter diagram of air permeability coefficient of all ratio and total porosity, which is shown in Fig. 1.

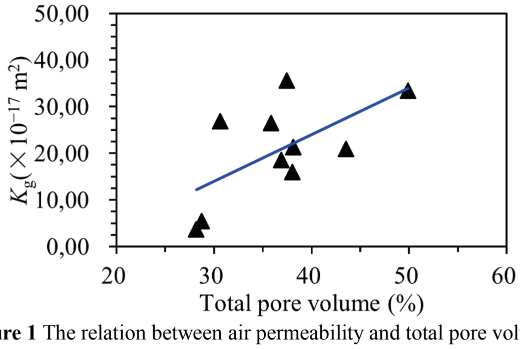

Figure 1 The relation between air permeability and total pore volume of SHPC

It can be found, based on experience, the greater the total porosity in concrete, the higher the permeability. However, Fig. 1 shows: the correspondence between air permeability coefficient of SHPC and total porosity is scattered and the linearly dependent coefficient is 0,63. Based on simplified capillary model, the total porosity can characterize air permeability only if confirming the diameter distribution. Therefore, we cannot exclusively use the total porosity of SHPC to characterize its air permeability.

4.2 Correlation between air permeability and parameter representing pore diameter distribution

The author draws the relationship scatter diagram of air permeability coefficient of SHPC and characterization pore diameter distribution characteristics parameter based on experimental results.

4.2.1 Correlation between SHPC air permeability and mean pore diameter

Fig. 2 shows that the correlation between SHPC air permeability and mean pore diameter is not too evident. And the linear fitting conducted reveals that the linearly dependent coefficient between SHPC air permeability and mean pore diameter is 0,37. Therefore, for SHPC, mean pore diameter may characterize its air permeability. The overall tendency is that the greater the mean pore diameter, the higher the air permeability. However, the linearly dependent coefficient is relatively low.

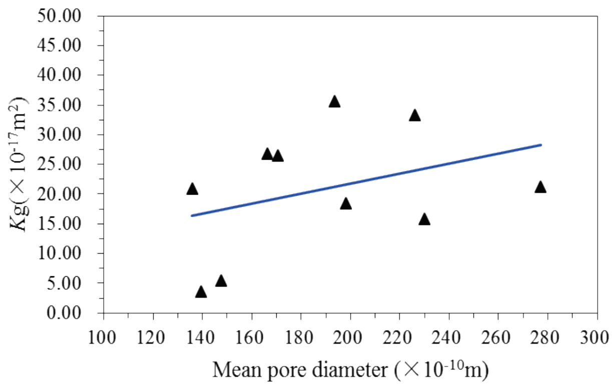

Figure 2 The relationship diagram of SHPC air permeability and mean pore diameter

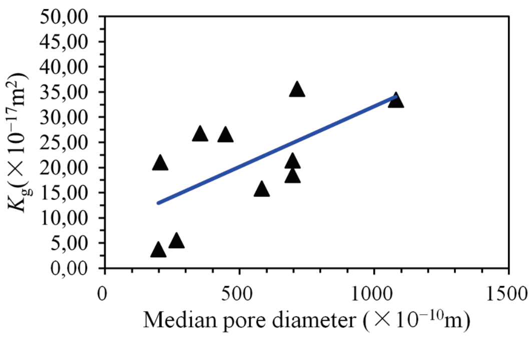

Figure 3 The relationship diagram of SHPC air permeability and median pore diameter

4.2.2 Correlation between SHPC air permeability and median pore diameter

Fig. 3 shows that the SHPC air permeability and median pore diameter shows a good correlation and the linear fitting conducted reveals that the linearly dependent coefficient between SHPC air permeability and median pore diameter is 0,64, which shows that median pore diameter can characterize SHPC air permeability.

4.2.3 Correlation between SHPC air permeability and threshold pore diameter

Figure 4 shows that the SHPC air permeability and median pore diameter show good correlation and the linear fitting conducted reveals that the linearly dependent coefficient between SHPC air permeability and median pore diameter is 0,69. In this experiment, the number of SHPC samples is 10. According to the checklist of correlation coefficient, we set the significance level α=0,10. When the sample number is 10, the critical value of testing correlation coefficient ρ=0 is 0,5494. Therefore, there exist linear correlations between SHPC air permeability coefficient and threshold pore diameter. This experiment reveals that the threshold pore diameter can be used to characterize the SHPC air permeability, i.e. the greater the threshold pore diameter, the higher the SHPC air permeability.

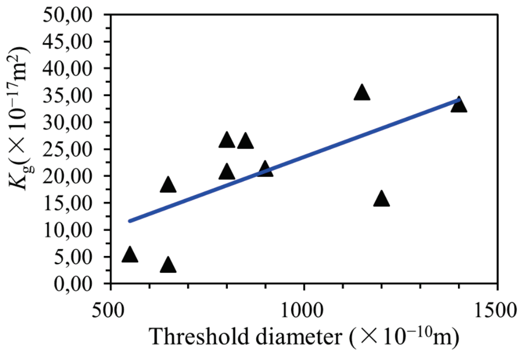

Figure 4 The relationship diagram of SHPC air permeability and threshold pore diameter

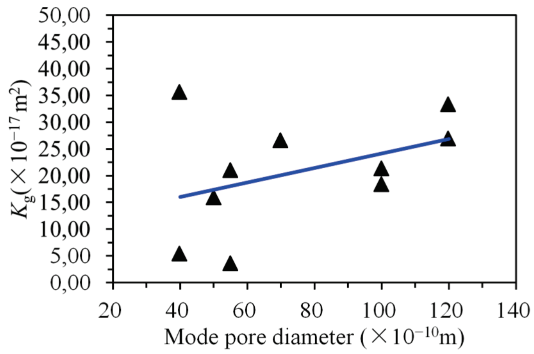

Figure 5 The relationship diagram of SHPC air permeability and mode pore diameter

4.2.4 Correlation between SHPC air permeability and mode pore diameter

Fig. 5 shows that the correspondence between SHPC air permeability coefficient and mode pore diameter is relatively scattered and the linear fitting conducted reveals that the linearly dependent coefficient between SHPC air permeability coefficient and mode pore diameter is 0,4. The experiment shows that the air permeability has tendency to increase with the increase of mode pore diameter, but this tendency calls for more experiments to testify. The exclusive use of mode pore diameter cannot characterize SHPC air permeability.

4.3 Correlation between SHPC air permeability and pore surface area

Fig. 6 is a scatter diagram showing the correlation between SHPC air permeability and pore surface area. The data points are scattered without any rule, so the pore surface area cannot reflect air permeability. However, SHPC air permeability tends to decrease as the surface area increases, which is still to be verified through theory and experiment.

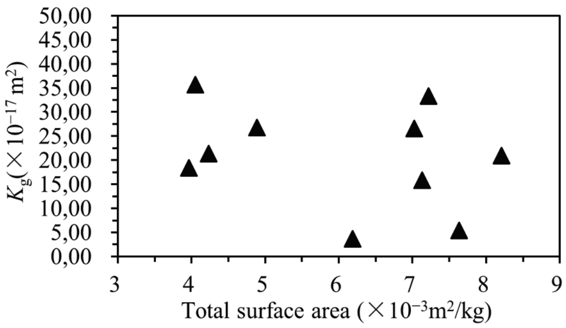

Figure 6 The relationship diagram of SHPC air permeability and pore surface area

5 Conclusion

The author, based on air permeability experiment and mercury injection experiment, analyses correlation between parameters of pore structure and SHPC air permeability. The following conclusions are acquired:

1) The mean and mode pore diameters of SHPC are poorly correlated to air permeability without certain relation, thus unable to represent air permeability of SHPC.
2) The median pore parameter and threshold parameter of SHPC are certainly correlated and thus can represent air permeability. The general correlation trend is that with larger median pore parameter and threshold parameter, air permeability of SHPC is higher.
3) The SHPC total porosity is certainly correlated to air permeability and can only represent air permeability by itself when pore diameter distribution is nearly the same.
4) The SHPC surface area is not certainly correlated to air permeability, and thus cannot represent air permeability. However, SHPC air permeability tends to decrease as the surface area increases, which is still to be verified through theory and experiment.
5) The pore distribution parameter, as a representative of air permeability, can only show one trend approximately. Based on pore structure parameters, the representative model for SHPC air permeability involving several factors is to be built, which requires further study on distribution rule of pore structure diameter and verification through more experiments on concrete test piece.

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