XVI International Conference on Durability of Building Materials and Components
DBMC 2023, China
K.F. Li and D.P. Fang (Eds)

Service Life Prediction of Concrete Against Freezing and Thawing Based on Water Absorption Results

Lei Xu[1], Junjie Wang[*1], Chenyang Zhang[2], Zhe Li[1] and Qi Yang[1]

[1]Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China, xl21@mails.tsinghua.edu.cn (Lei Xu), junjiewang@tsinghua.edu.cn (Junjie Wang, Corresponding author), lizhequt@163.com (Zhe Li), ayyqbonjour@gmail.com (Qi Yang)

[2]Zhejiang Provincial Seaport Investment & Operation Group Co. Ltd, zcy.x@foxmail.com

Abstract. *Freezing and thawing resistance performance of concrete is a critical issue when evaluating the durability performance of concrete. This paper aims to predict the freezing and thawing resistance performance of concrete based water absorption indexes, meanwhile, five groups of experiments on porosity, short-term water absorption, long-term water absorption, MIP and pore structure scanning were respectively carried out for concrete. According to the experimental results, the important indexes such as porosity, water absorption, gas content and bubble spacing coefficient were obtained, which provided the basis for the prediction of durability and service life. The concept of equilibrium time ratio is introduced to simplify the calculation process. Based on the critical saturation theory, the service life of concrete against freezing and thawing is predicted by combining the environmental parameters and the indexes measured in experiments. The calculated results verified that the freeze-thaw durability life of air-entrained concrete is significantly increased compared with that of concrete without air-entrained concrete. In addition, a wide range of the service life was predicted for the 5 mixes, and the results could provide a guidance for selecting a proper mix design of concrete subjected to freezing and thawing.*

Keywords: *Air-entrained Concrete, Freezing and Thawing, Water Absorption, Durability, Service Life.*

1 Introduction

Concrete, as the most significant building material presently and potentially in the future, requires intense analysis of its soundness to ensure building structures' safety and cost-effectiveness. In regions with freezing temperatures, the durability of concrete concerning freezing and thawing is critical. Based on extensive research, two primary factors cause the failure of concrete during freeze-thaw cycles: the development of internal cracks and the removal of the concrete surface, mostly when deicing agents are in use (Pigeon et al. 1996). The freezing of water within concrete creates an increase in volume by approximately 9%, leading to stress and eventual cracking, in the absence of adequate space in the concrete. Due to surface tension, water freezes in larger pores before smaller internal ones, exerting a destructive force that results in ice-free supercooled water migrating between concrete internal pores. The difference in ion concentration arising from freezing increases the water migration due to osmotic pressure, worsening the damage. If the stress from the cracking surpasses the concrete's strength, micro-cracks occur, which expand with continued freeze-thaw cycles, leading to reduced strength and consequential harm (Xu et al. 2022). Spalling is primarily caused by the cracking and peeling of cementitious material from the concrete surface. The damaged structure of the surface layer makes it easier for water and ions to penetrate the concrete, resulting in worsened damage, thus significantly affecting its durability (John et al. 2007).

With the understanding of the crucial saturation point of concrete, this study investigates the freeze-thaw resistance of concrete. The investigation commences by analyzing the water absorption process of concrete, with critical saturation being the benchmark to identify the decline in freeze-thaw resistance. To achieve this goal, the long-term water absorption model and water saturation calculation model of concrete are amalgamated. The study determines the durability parameters through diverse experiments. By utilizing the concrete dry-wet alteration model, this paper predicts the durability of concrete and offers valuable suggestions for selecting the mix ratios of antifreeze and thawing concrete.

2 Materials and Methods

2.1 Raw Materials

The cement utilized in this study is classified as P.O 42.5 ordinary Portland cement. The coarse aggregates were carefully selected and sorted into two fractions: larger gravel measuring 16-31.5 mm in diameter and smaller gravel measuring 4.75-16 mm in diameter, and both were well-graded. The fine aggregates employed in this study consist of natural sand (0-4.75 mm), possessing a fineness modulus of 2.3. The fiber utilized ultra-high strength modified polyester synthetic fiber. The superplasticizer employed is classified as an air entraining polycarboxylic acid water-reducing agent.

2.2 Mix Design and Specimen Preparation

The amount of cement used is 330 kg/m³. In order to ensure the homogeneity of the concrete mixture, it was blended using a forced mixer (BHS double horizontal shaft 60 liter concrete mixer). The samples were filled at once during the formation process and then placed on a vibration table for 10 seconds. Following vibration, the surface of the samples was smoothed using a trowel, and the samples were water-cured at 20 °C after being removed from the mold at 24 hours. The concrete mix was divided into five groups (G1-G5) based on the fiber content and whether a water-reducing agent was used. The mixing proportions and relevant composition information for each group are presented in Table 1.

Table 1. Concrete mix ratios.

Number	G1	G2	G3	G4	G5
Sand (kg/m³)	609.42	611.4	611.4	611.4	611.4
Coarse aggregate (kg/m³)	782.09	784.63	784.63	784.63	784.63
Fine aggregate (kg/m³)	639.89	641.97	641.97	641.97	641.97
Water (kg/m³)	138.6	132	132	132	132
Superplasticizer (kg/m³)	0	6.6	6.6	6.6	6.6
w/b	0.42	0.4	0.4	0.4	0.4
Sand ratio	0.3	0.3	0.3	0.3	0.3
Fiber (kg/m³)	0	0	1	1.4	1.8

2.3 Experimental Method

The experiments in this paper refer to the corresponding specifications of each experiment, and the size of the test piece is different. The size of the porosity test is a cube with 75mm side length, and three blocks are made for each group. The average value of the experimental results is taken to reduce the error and ensure the accuracy of the experimental results. The standard concrete water absorption measurement method recommended by ASTM C1585, while the size of the test block selected in this paper is 100×100×50mm. The size of long-term immersion water absorption test piece is the same as that of single-sided water absorption test piece. After the water absorption test of concrete is completed, the test block is used as the pore structure scanning.

2.3.1 Porosity test

The total porosity of hardened concrete was measured according to the weight method recommended in CCES 01-2004. Insert the cut test block into the vacuum water saturation machine, and fill it with vacuum water. Once finished, submerge the block in water and use an electronic balance to measure the block' s buoyancy. After removing any free water on the surface of the test block with a cloth, determine the saturated mass of the block. Proceed by drying the test block completely using an oven, and remove it when the weekly mass change is below 1%. Finally, weigh the dry mass of the block by placing it into a dryer containing blue silica gel until it naturally cools down to room temperature.

2.3.2 Short-term and long-term water absorption test

The determination of short-term water absorption is based on ASTM C1585, which recommends a single-sided water absorption test. Mass is measured after water absorption at designated time intervals, including 60 seconds, 5 minutes, 10 minutes, 20 minutes, 30 minutes, 60 minutes, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, 1 day, 2 days, 3 days, 4 days, 5 days, 6 days, 7 days, and 8 days. During the test, the contact surface is wiped with a damp cloth to remove any moisture and returned to the testing environment promptly to ensure the accuracy of the results. The precautions for the long-term immersion water absorption experiment are similar to those of the single-sided water absorption experiment. However, due to the absorption caused by immersion, the side and top surfaces are left untreated, and the measurement time is more extended. The measurement time intervals correspond to those of the short-term water absorption test, and daily quality measurements are conducted after 1 day.

2.3.3 Pore structure scanning

The MIC-840-01 hardened concrete pore structure tester is employed to conduct the pore structure scanning experiment, capable of detecting pores with a diameter ranging from 10 to 2000 microns. The experimental scanning area is set to 90×90 mm to enhance the representativeness of the test results. instrument used in the pore structure scanning experiment is MIC-840-01 type hardened concrete pore structure tester.

2.3.4 Mercury intrusion porosimetry

The pore size distribution was measured through MIP (Autopore IV 9510, U.S.A) for mercury pressures up to 414 MPa. For details of the experiment, see our previous research (Xu et al. 2023).

3 Results and Analyses

3.1 Porosity Test

The porosity of concrete can be calculated according to the measured data, and the porosity of each test block can be calculated using the formula (1).

$$\varphi_i = \frac{m_s^i - m_d^i}{m_s^i - w_b^i} \tag{1}$$

Where, m_s^i is the saturated mass of the numbered sample, m_d^i is the dry mass, and w_b^i is the floating weight in water.

The average value of the calculation results shows that the total porosity of G1-G5 is 9.7%, 11.4%, 12.4%, 11.4% and 11.7% respectively. And the total porosity of G1-G5 measured by MIP is 10.174%, 18.015%, 15.833%, 16.143% and 15.919%, respectively.

3.2 Short-term Water Absorption Test

The water absorption amount of concrete is obtained by subtracting the initial mass of concrete from the measured concrete mass at each time, divided by the water absorption area. Take the square root of time as the x-axis, and the water absorption as the y-axis, draw the I-diagram, and perform linear regression with the least square method for the scattered points within 0-6h, and the correlation coefficient R^2 are very close to 1, indicating that the water absorption curve has a good fitting effect. The first water absorption (S_1) of each group of concrete can be obtained, which is the slope of each regression line, which is 3.3, 2.6, 3.1, 6.2, 4.2 (10^{-3}mm/$s^{0.5}$). Carry out linear regression with the least square method for the scattered points within the time range of 1-7d, as shown in the figure. Similarly, the correlation coefficient R^2 are very close to 1, and the second water absorption rate (S_2) of each group of concrete can be obtained, which is the slope of each regression line, respectively 1.8, 1.4, 1.6, 2.2, 1.4 (10^{-3}mm/$s^{0.5}$)

3.3 Pore Structure Scanning Test

According to the results of concrete pore structure scanning test, a series of data about pore distribution of each group of concrete can be obtained. The bubble spacing factor of G1-G5 is 209.94, 134.48, 119.82, 145.59 and 139.63 μm, respectively. The gas content (the range of pore radius is between 10 and 800 μm) of G1-G5 is 1.59, 5.49, 5.90, 4.81 and 6.54%, respectively. The specific surface area of G1-G5 is 0.037, 0.033,0.035,0.032,0.027 1/μm, respectively.

The instrument used in the pore structure scanning experiment can measure pores larger than 10 μm. By analyzing the experimental results, it is found that G1 pore diameter is mainly distributed in 10-120, accounting for 90%, and G2 pore diameter is mainly distributed in 10-200, accounting for 91%. The pore distribution of other concrete is similar to that of G2. When the bubble spacing coefficient of air-entrained concrete is less than 0.2, it can better improve the freeze-thaw resistance of concrete (Zeng, 2012). Therefore, based on the experimental results, the air content of the concrete in G2-G4 after adding water reducing agents for air entrainment is significantly increased, and the bubble spacing coefficient is less than 0.2, which will enhance its frost resistance.

4 Prediction of Freeze-thaw Durability

According to the experimental results described in section 3, the parameters required for some models can be obtained. Including short-term water absorption (first water absorption), total porosity (using MIP results), gas content, etc. In addition, there are still some parameters to be calculated.

When the air in the bubble dissolves and diffuses, the diffusion coefficient in the slurry can be calculated according to the formula (2) (Yokozeki et al. 2010).

$$D_e = \frac{1 - cv_{ca}}{1 - dv_{fa}} v_{paste} f(\varphi) D_0 \tag{2}$$

Where D_0 is the diffusion coefficient of air in water, $D_0 = 2 \times 10^{-9} m^2/s$, v_{ca} , v_{fa} , respectively, are the proportion of coarse and fine aggregate volume, c, d is the correction coefficient, taken as 1.5 and 0.86. The tortuosity is:

$$f(\varphi) = 0.001 + 0.07\varphi^2 + 1.8(\varphi - 0.18)^2 \times H(\varphi - 0.18) \tag{3}$$

Where H is the Heaviside Function. The tortuosity and diffusion coefficient can be obtained by calculation.

According to the results of pore structure scanning experiment, the two-dimensional distribution of pore size in concrete conforms to the form of power function. In order to simplify the calculation, the pores are regarded as spherical and the three-dimensional distribution of pores is expressed in the form of power function (Fagerlund, 1993). Let the number of pores with radius R per unit volume be:

$$f(R) = a_1 \frac{1}{R^b} \tag{4}$$

Where a_1， b are parameters. By integrating the above formula, we can get:

$$a_0 = \int_{R_{min}}^{R_{max}} \frac{4\pi R^3}{3} f(R) dR \tag{5}$$

$$\alpha = \frac{\int_{R_{min}}^{R_{max}} 4\pi R^2 f(R) dR}{\int_{R_{min}}^{R_{max}} \frac{4\pi R^3}{3} f(R) dR} = 3 \frac{\int_{R_{min}}^{R_{max}} R^{2-b} dR}{\int_{R_{min}}^{R_{max}} R^{3-b} dR} \tag{6}$$

Where a_0 is the gas content and α is the average specific surface area of pores. The parameters a_1 and b can be calculated from the above two formulas. The minimum value $Rmin$ of the specified pore radius is 10 μm, because the pores above 10 μm are not filled in the process of capillary water absorption (Fagerlund, 1993). The maximum value $Rmax$ is taken as the aperture of 99% of the total number of holes.

Other parameters are general parameters under standard conditions: solubility of air in water $s = 2.4 \times 10^{-7} kg/(m^3 \cdot Pa)$, air density $\rho_0 = 1.225 kg/m^3$, surface tension of water $\sigma = 0.074 N/m$. The relevant concrete parameters are calculated and sorted out as shown in Figure 1.

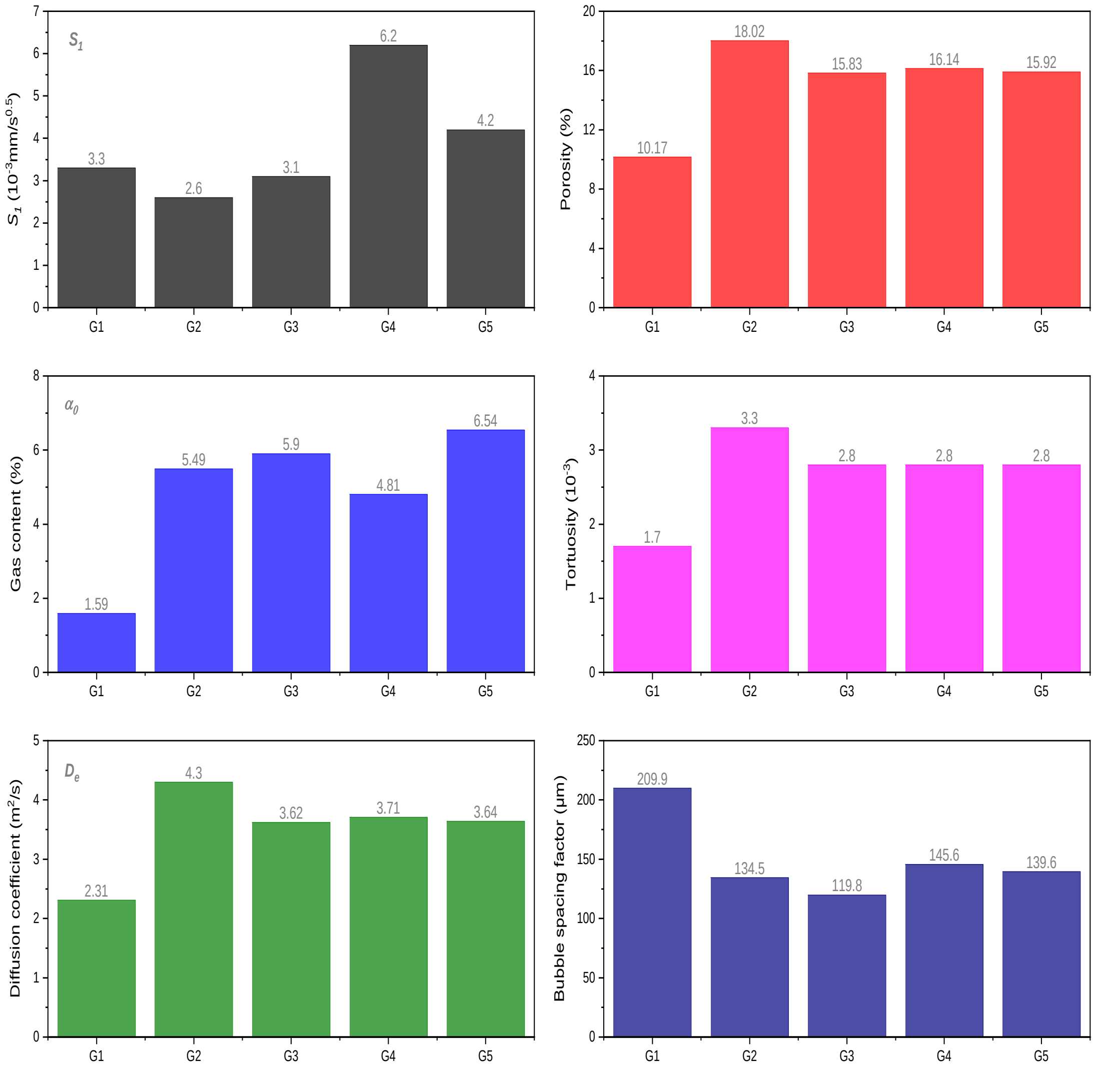

Figure 1. Relevant parameters of concrete durability prediction.

Assuming the relative humidity of the environment of 57%, combined with the water vapor isothermal adsorption-desorption curve of the concrete, the equilibrium water saturation can be obtained as 0.3 (Gui, 2016). When calculating the drying depth, the parameter λ can be calculated by the following formula (Li, 2009).

$$\lambda \operatorname{erf}(\lambda) \exp(\lambda^2) = \frac{1}{\sqrt{\pi}} \frac{p_{vs}}{\rho_l} \frac{M_v}{RT} (h_s - h_0) \tag{7}$$

Where R is the ideal gas constant $(J/mol \cdot K)$, T is the absolute temperature (K), p_{vs} is the saturated vapor pressure (Pa), ρ_l is the density of water (kg/m^3), and M_v is the molar mass of water vapor (kg/mol). It is calculated that $\lambda = 0.0019$. The balance time ratio τ_s of G1-G5 are calculated and the results are respectively 352, 117, 198, 773, 362.

Generally, even if the weather is rainy on a certain day, the precipitation will not last for a whole day. Moreover, the water absorption rate of concrete will be significantly reduced after 6 hours of water absorption (Castro et al. 2011). The previous short-term single-sided water absorption can also reflect this situation. Therefore, in the calculation, it is specified that the continuous wetting time of concrete is 6h for each rainy day.

After obtaining all the above parameters, we can start to predict the freeze-thaw durability of concrete. The critical water saturation is taken as 0.85. When the water saturation of concrete at a certain time $S_t \geq S_{cr} = 0.85$, it is considered that it will lose its freeze-thaw durability, and the time t is the freeze-thaw durability life of concrete. The expected life of concrete freeze-thaw durability calculated by the formula is less than 1, 57, 94, 82, 249 years, respectively.

5 Conclusions

- This paper combines the actual environmental parameters of the geographical environment, the calculation model of concrete water saturation, the calculation and analysis method of equilibrium time ratio under the action of dry and wet cycles, and the data obtained from various micro and macro tests of concrete. Based on the critical water saturation theory of concrete freeze-thaw damage, the expected freeze-thaw damage durability of various mix proportions of concrete in a specific regional environment is calculated.
- Compared with non-air-entraining concrete, air-entraining concrete can greatly improve the freeze-thaw durability of concrete, and the time to reach the critical water saturation is increased from less than a year to decades. It is sufficient to meet the needs of its service life. As an effective method to improve the durability of concrete against freezing and thawing, air entrainment should be widely promoted in areas and projects with high requirements for concrete frost resistance.

Acknowledgements

The authors wish to acknowledge the financial support provided by the National Natural Science Foundation of China (Nos. 52008232, 52038004).

ORCID

Lei Xu: http://orcid.org/0000-0001-9674-9689
Junjie Wang: http://orcid.org/0000-0002-1148-777X

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