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STUDY ON THE DAMAGE MECHANISM OF PORE STRUCTURE IN CONCRETE SUBJECTED TO FREEZE-THAW CYCLES

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ABSTRACT

It is well know that freeze-thaw cycles play the most significant role in the durability evolution in concrete structures, freeze-thaw cycles have been accounted as one of the major factors on the damage and demolition of concrete. Microscopic parameters have been used for describing the characterizations of damage in concrete under freeze-thaw actions by researchers. However, their models could not provide specific damage factors or parameters. In this paper, a new damage model and equation based on variations of pore structure in concrete is established. This new pore damage model is used for analysing freeze-thaw damage of concrete and validated by experiments. The results show that the measurement of pore structure becomes larger, the diameters of most probably pore structure, critical pore structure, and the variations of porosity increase with the process of freeze-thaw cycles. The pore damage factor or parameter is suitable for describing the mechanism of freeze-thaw damage. Furthermore, the damage results calculated by this new freeze-thaw damage equation, based on variations of pore structure in concrete gives an excellent correlation with experimental results. This pore damage equation was proved to be effective for evaluating the degradation of concrete which is subjected to freezing and thawing cycles in low or sub-zero regions.

KEYWORDS

Concrete; freeze-thaw cycles; pore structure; damage mechanism

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INTRODUCTION

In the low or sub-zero climate regions, freeze-thaw damage is the most significant durability problem in concrete structures. At present, researchers focused on studying the freezing and thawing damage mechanism for improving the frost resistance of concrete. In the recent 50 years, a lot of advanced technologies were applied for improving the frost resistance of concrete. One of the advanced technologies was the development of entrained air in concrete [1]. The entrained air can improve the frost resistance durability of concrete material and enhance lifetime of concrete structures. However, the durability problems of air entrained concrete are still serious [2-5].

Studies on concrete behaviour subjected to freeze-thaw cycles primarily focused on damage and degradation mechanism of concrete based on experimental methods. The properties of concrete material such as weight loss, relative dynamic modulus and compressive strength were used for evaluating the damage of concrete caused by freezing and thawing cycles. Song et al. [6] tested the relative dynamic modulus and weight loss of concrete after freeze-thaw cycles by quick freeze-thaw method and discovered that the ranges of relative dynamic modulus and weight loss of concrete subjected to freeze-thaw cycles were small and the relative dynamic modulus of concrete maintained high value. Yu et al. [7] found that the changes of relative dynamic modulus and compressive strength of concrete subjected to different freezing thawing cycles were only suitable for describing one stage of the whole degradation progress of concrete. The ordinary damage parameters of concrete material were not suitable and precise for describing freezing and thawing damage mechanism of concrete material.

Researchers started to pay attention on mesoscopic freeze-thaw damage mechanism of concrete. When concrete structures or concrete sample were exposed to freeze-thaw or de-iced pore solution in concrete changes into ice and expanded by approximately 9% volume. Because of the expanded volume of frozen solution, unfrozen solution was promoted to any available side in concrete material. The restrained moving of unfrozen pore solution produced hydraulic pressure. When the maximum hydraulic pressure exceeded the limit extension and compressive strength of concrete, the pore structure changes. Producing, a lot of microcracks were produced due to the expansion of pore structures. Variations of pore structures in concrete exposed to freeze-thaw cycles caused degradations of concrete properties. However, there were few studies on proposing or testing the relationship between changes of pore structure and damage or degradation mechanism of concrete material subjected to freeze-thaw cycles. The relationship between variations of pore structure and freeze-thaw damage or degradation characterizations of concrete material is studied in this paper by modelling and testing. The characterizations of pore structure and compressive strength were obtained by experiments and the pore damage equation for the degradation mechanism of concrete is proposed.

METHODS

Materials

In this test, ordinary Portland cement was used. The crushed stone with the size between 5mm to 31.5mm was used as the coarse aggregate, and natural stand was used as the fine aggregate. The physical properties of the concrete are given in Tab. 1.

Tab. 1. Physical Properties of Concrete Material

Slump	Air content	28-day compressive strength	28-day bending strength
160 mm	4.5 %	55.8 MPa	6.8 MPa

Seven prisms with size of 400mm×100mm×100mm were casted. The mixing properties of concrete are shown in Tab. 2.

Tab. 2. Mixing Proportions of Concrete Material

Water	Cement	Natural sand	Crushed stone	Water cement ratio	Sand ratio
157 kg	393 kg	692.6 kg	1124.9 kg	0.4	38 %

The specimens were produced during 24 hours and were cured for 28 days according to the GB/T 50081-2002 (NSPRC 2002).

Test Methods

The rapid freeze-thaw test was conducted according to GB/T 50082-2009 (NSPRC 2009). The controlled temperature of the concrete specimens was changed in the range -18 ± 2 °C to 5 ± 2 °C in one cycle, and the duration of single cycle was 2 to 4 hours. At each end of 50, 100, 150, 200, 250 and 300 freeze-thaw cycles, the specimens were taken out of the freeze-thaw machine and wiped off. The values of compressive characterizations of pore structures of concrete specimens were tested by dynamic press machine and mercury intrusion porosimetry (MIP) method. The mechanical properties tests were performed according to GB/T 50081-2002 (NSPRC 2002).

Pore Damage Model of Concrete subjected to freeze-thaw cycles

A variety of damage mechanism or models of concrete subjected to freeze-thaw cycles were proposed by a series of studies or experiments [8-15]. Among these degradation models, the hydrostatic pressure and osmotic pressure hypothesizes proposed by Powers were ones of high recognition theories for describing the freeze-thaw mechanisms of concrete. However, these models only considered the degradations of macroscopic and physical properties of concrete, and their damage factors were only suitable for their own damage models. Furthermore, freeze-thaw damage mechanism or models of concrete have not yet been commonly concluded.

Over the past decades, the mesoscopic structural changes in concrete had been proposed to describe the freeze-thaw damage mechanism of concrete. The pore structure in concrete expands to strength reduced in concrete material after freezing and thawing cycles. The mechanical properties of concrete were essentially influenced by the changes of pore structure in concrete. Zhang et al. [16] found that characterizations of pore structure in concrete were associated with frost resistance of concrete. Meng [17] found that excellent properties of pore structure provided excellent frost resistance durability of concrete. Although there were some experimental and theoretical models on studying the microstructural freeze-thaw damage, the pore structure damage factor for describing the properties of concrete after repeated freeze-thaw cycles has not been proposed yet.

Wittmann et al. [18] propounded pore theory for plotting apertures of pore structures in concrete, and found that different apertures of pore structure had different important influence on the properties of concrete. Wu et al. [19] found that capillary and air voids had significant impact on frost resisting of concrete. The characterizations of capillary voids in concrete subjected to freeze-thaw cycles are studied in this paper. A relationship between freeze-thaw cycles and evolutions of pore structure can be established by considering this deterioration:

$$\frac{d(R\text{-}R_0)}{dR_0}=\alpha(N) \qquad (1)$$

where: N is the number of freezing and thawing cycles;

R and R_0 are capillary pore size after freeze-thaw cycles and without freeze-thaw cycles;

α is fitting function.

This pore size after freeze-thaw cycles can be solved from Eq. (2):

$$R=(1+e^{\alpha(N)})\ R_0 \qquad (2)$$

The pore damage factor is defined as:

$$D_P=\frac{(1+e^{\alpha(N)})\ R_0}{R_0}\text{-}1 \qquad (3)$$

Freeze-Thaw Damage Model of Concrete

The damage parameter of concrete material was proposed as follows:

$$\omega=1\text{-}[\frac{\sum_{i=R_{\min}}^{R_{\max}}(1+e^{\alpha(N)})\ R_0}{\sum_{i=R_{\min}}^{R_{\max}}R_0}\text{-}1] \qquad (4)$$

where: ω is damage parameter of concrete material after freeze-thaw cycles;

R_{max} and R_{min} are maximum and minimum capillary pore size after freeze-thaw cycles.

The compression stress of concrete material can be calculated by using the proposed damage Eq. (4) as follows:

$$\sigma_{cN}=\{1\text{-}[\frac{\sum_{i=R_{\min}}^{R_{\max}}(1+e^{\alpha(N)})\ R_0}{\sum_{i=R_{\min}}^{R_{\max}}R_0}\text{-}1]\}\sigma_{c0} \qquad (5)$$

where: σ_{cN} is the compression stress of concrete material subjected to freezing and thawing cycles;

σ_{c0} is the compression stress of concrete material without freezing and thawing cycles.

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The compressive strength and elasticity modulus can be calculated as follows:

$$f_{cN}=\{1-[\frac{\sum_{i=R_{\min}}^{R_{\max}}(1+e^{\alpha(N)})\ R_0}{\sum_{i=R_{\min}}^{R_{\max}}R_0}-1]\}\,f_{c0} \tag{6}$$

$$E_N=\{1-[\frac{\sum_{i=R_{\min}}^{R_{\max}}(1+e^{\alpha(N)})\ R_0}{\sum_{i=R_{\min}}^{R_{\max}}R_0}-1]\}E_0 \tag{7}$$

where: f_{cN} is compressive strength of concrete subjected to freeze-thaw cycles;

f_{c0} is compressive strength of concrete without freeze-thaw cycles;

E_N is elasticity modulus of concrete subjected to freeze-thaw cycles;

E_0 is elasticity modulus of concrete without freeze-thaw cycles.

RESULTS

Changes of pore structures in concrete subjected to freeze-thaw cycles

With the increasing numbers of freeze-thaw cycles, the internal pore structure of concrete continuously expanded, and formed strips of micro-cracks. The characteristics of pore structure in concrete subjected to freeze-thaw cycles such as porosity, most probably pore size and critical pore size were shown in Tab. 3.

Tab. 3 Characterizations of Pore Structure in Concrete

Freeze-thaw cycles，N	0	50	100	150	200	250	300
Porosity（%）	23.17	23.23	23.39	23.53	23.57	23.83	24.32
Most probably pore size（nm）	40.28	42.35	45.16	46.73	49.48	51.21	54.94
Critical pore size（nm）	45.30	49.70	53.90	55.20	58.40	60.10	63.80

Changes of porosity of concrete after freeze-thaw cycles

Zhao et al. [20] found that the values of porosity indicate that the total volume values of pore structures in concrete. The changes of concrete porosity are shown in Fig. 1.

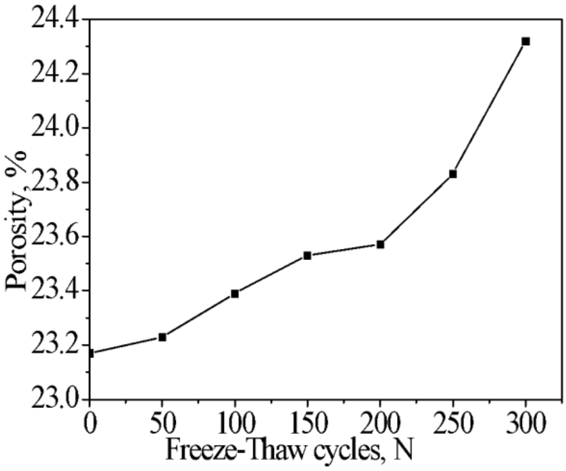

Fig. 1. Porosity of concrete subjected to freeze-thaw cycles

With increasing number of freeze-thaw cycles, the value of concrete porosity increased from 23.17% to 24.32%. The value of concrete porosity increases 4.73%. The characterizations of concrete porosity represented the changes of total volume of pore structures in concrete. The changes of porosity of concrete are not suitable for representing the changes of capillary pore structure and describing the frost damage of concrete.

Changes of most probably pore size and critical pore size after freeze-thaw cycles

Feng et al. [21] found that the values of most probable pore size was appropriate for characterizing the properties of concrete. However, the critical pore size is also a significant parameter for describing the properties of concrete after freeze-thaw cycles. In this study, the characterizations of most probably pore structure and critical pore structure are used for proposing frost damage equations. The values of most probably pore size and critical pore size are shown in Fig. 2 and Fig. 3.

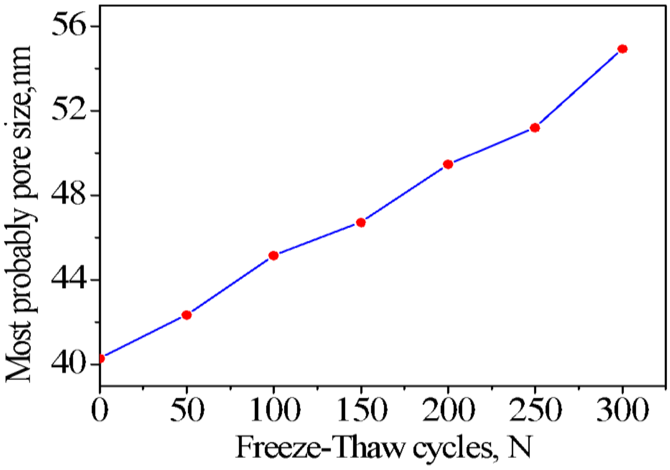

Fig. 2. Most probable pore size of concrete subjected to freeze-thaw cycles

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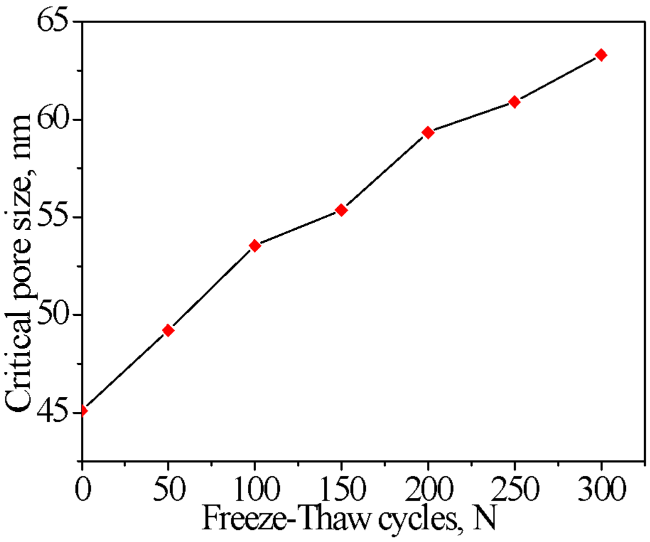

Fig. 3. Critical pore size of concrete subjected to freeze-thaw cycles

The values of most probably pore size and critical pore size increased 36.40% and 40.84% at the end of 300 freeze-thaw cycle, respectively. With the increasing number of freeze-thaw cycles, the internal pore structure of concrete expanded and the expansion of concrete pore structure accumulated damage.

The damage factors of most probably pore structure and critical pore structure can be calculated by equation 3. The damage values are shown in Tab. 4 and the damage values can be proposed by two different fitting cures as follows:

$$D_{M-P} = \frac{A \times N^B}{100} \tag{8}$$

$$D_{C-P} = \frac{A_1 \times e^{(-N/t_1)} + A_2 \times e^{(-N/t_2)} + A_0}{100} \tag{9}$$

where: $D_{M\text{-}P}$ is the damage factor of most probable pore structure;

A and *B* are fitting coefficients, A = 0.507, B = 0.770;

$D_{C\text{-}P}$ is the damage factor of critical pore structure;

A_0, A_1, A_2, t_1, t_2 and t_3 are fitting coefficients, A_0 = -128.910, A_1 = 129.402, A_2 = 4.413E-11, t_1 = -1300.449, t_2 = -12.156.

Tab. 4 Damage Factors of Most Probable Pore size and Critical Pore Size

Freeze-thaw cycles, N	0	50	100	150	200	250	300
D_{M-P}	0	5.14%	12.16%	16.01%	22.84%	27.14%	36.40%
D_{C-P}	0	9.71%	18.98%	21.85%	28.92%	32.67%	40.84%

Analysis on freeze-thaw damage of concrete

In analysis of the veracity of the proposed freeze-thaw damage model in this paper, the Duan model [22] and the proposed pore damage models results are used to compare with the results of experiments subjected to different freeze-thaw cycles. The Duan model is based on experimental and empirical analysis and was following from:

$$f_{cu}=33.1MPa,\frac{f_{cD}}{f_{c0}}=1-0.0051N$$
$$f_{cu}=37.5MPa,\frac{f_{cD}}{f_{c0}}=1-0.0029N$$
$$f_{cu}=46.8MPa,\frac{f_{cD}}{f_{c0}}=1-0.0021N \tag{10}$$

where: f_{cu} is 28-day ultimate compressive strength;

N is number of freeze-thaw cycles;

f_{cD} is compressive strength of concrete subjected to different freeze-thaw cycles;

f_{c0} is compressive strength of concrete without freeze-thaw cycles.

The compressive strength values calculated by the Duan model, proposed pore damage model and the experimental results after different freeze-thaw cycles are shown in Fig. 4.

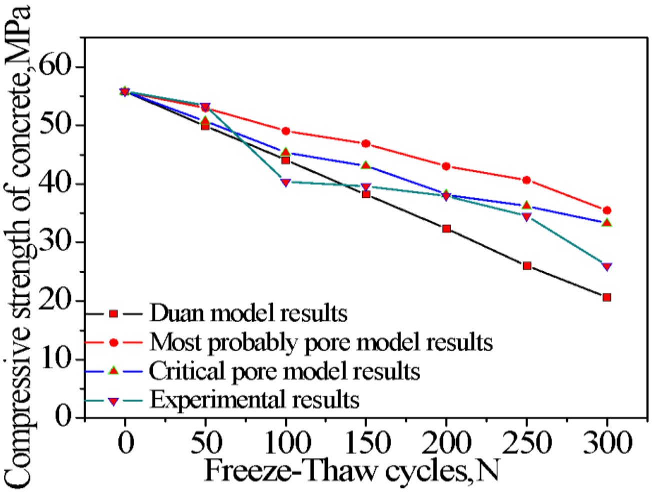

Fig. 4. Compressive strength of concrete subjected to freeze-thaw cycles

The experimental compressive strength decreased from 55.8MPa to 26.05MPa. The decreased compressive strength results calculated by the proposed pore damage models are 20.31MPa and 22.53MPa, respectively.

Tab. 5 shows the differences between calculated compressive strength by Duan model and proposed pore models and experimental results.

Tab. 5 Comparisons and Differences between the Calculated Results and the Experimental Results

Models and errors (MPa) Freeze-thaw cycles	Duan model	Most probably pore model	Critical pore model
0N	0	0	0
50N	-3.40	-0.41	-2.61
100N	+3.68	+8.65	+4.95
150N	-1.40	+7.29	+3.49
200N	-5.58	+5.12	+0.23
250N	-8.47	+6.15	+1.73
300N	-5.40	+9.44	+7.22

Note：+ indicated that calculated results were higher than experimental results; - indicated that calculated results were lower than experimental results.

Tab. 5 shows that the average errors of proposed pore damage models were 5.29MPa and 2.89MPa, the average error ratios are 15.45% and 8.47%, respectively. The proposed pore damage models seem suitable for describing the freeze-thaw damage of concrete.

CONCLUSION

On the basis of the experimental results and analysis of the proposed damage models, the following conclusions can be drawn:

1. The deterioration of compressive strength and the expansion of pore structure. With the increasing of freeze-thaw cycles, the compressive strength of concrete decreased 53.3%. The values of most probably pore size and critical pore size decreased 36.40% and 40.84%, respectively. The expansion of pore structure in concrete reduced the characterizations of concrete material.

2. The new freeze-thaw damage model. In this paper, a new damage model based on the expansion of pore structure was proposed for describing the degradations of concrete subjected to freeze-thaw cycles. The average error ratios of calculated results by using this proposed pore damage models were 15.45% and 8.47%, respectively. The changes of pore size were suitable for characterizing the damage factor of concrete.

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