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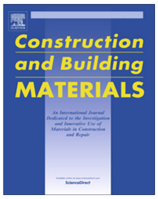

Characterization of air voids and frost resistance of concrete based on industrial computerized tomographical technology

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HIGHLIGHTS

- Industrial CT was used to measure the microscopic air voids of concrete.
- The parameters of air voids system were extracted from scanned images.
- The spacing factor was best correlated with the salt frost resistance of concrete.
- The air voids in air-entrained concretes were more stable under the freeze-thaw action.

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ABSTRACT

Air voids structure is the key parameter that affects the frost resistance of concrete, but traditional approaches of measuring the air voids of concrete are all destructive. This work utilizes the industrial computerized tomography to visualize the microstructure change during cyclic freeze/thaw test. The results indicate that the combination of industrial computerized tomography with subsequent image processing program can precisely measure the morphology and position of air voids in concrete. The air content measured by computerized tomography is slightly higher than that of traditional pore structure analyzer. The air content and spacing factor increase after cyclic freeze-thaw for both air-entrained and non-air-entrained concrete, and the variation rate of non-air-entrained concrete is several times that of air-entrained concrete. Besides, it can be directly observed from the reconstruction model that he air voids in air-entrained concrete experience no obvious expansion after cyclic freeze/thaw test, which increases the frost resistance of concrete.

1. Introduction

Frost damage and salt scaling are the major problems affecting the durability of concrete facilities in cold regions. In the past few decades, many researches have been conducted to solve these problems [1–4]. The mechanism of frost damage is that the absorbed water forms ice as the temperature drops below the freezing point, which causes 9% volume expansion. If the internal space of concrete cannot fit the volume expansion of water, a destructive stress occurs [5]. It has been found that the pore structure of concrete significantly affects its macro-properties such as strength [6,7], permeability [8] and deformation [9]. Thus, the surface deterioration caused by freeze-thaw cycles in de-icing salt environment is closely related to the distribution of micro-pores in concrete.

Currently, air-entraining agent (AEA) is commonly used to improve the frost resistance of concrete. Air voids in the hardened concrete can take ice-expansion stress and osmotic pressure that generated during freeze-thaw cycles. The increase of air content will reduce saturation of concrete and the time to reach equilibrium saturation, improving the frost resistance of concrete [10]. Referring to the suggestions of Powers [1], the average air voids spacing factor of high frost resistance concrete should not exceed 250 μm, which was also addressed in ACI 318 [11]. According to the technical guidelines for Construction of Highway Cement Concrete Pavements in China, the maximum spacing factor should be less than 225 and 275 μm for concrete pavement in frozen and cold areas respectively [12]. Both standards recommended a linear traverse method to measure the microstructure of concrete. However, the direction of guide line in the method is arbitrary, and the operation of optical microscope and the complicated preparation of test samples may introduce inevitable errors [13]. Besides that, the diameter and volume of air voids are also important factors that concrete with the air content about 6%±1% can effectively resist

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Table 1
Chemistry composition of cement.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	f-CaO
22.28	5.04	2.95	66.04	1.42	0.39	0.42	0.91

Table 2
Property index of sand.

Apparent density (kg/m^3)	Fineness modulus	Particle gradation							
		Sieve size (mm)	5.0	2.5	1.25	0.63	0.351	0.16	Bottom
2632	2.75	Residue (%)	1.8	7.1	19.9	25.3	34.2	10.9	0.8

Table 3
Property index of coarse aggregate.

Size (mm)	Apparent density (kg/m^3)	Accumulated density (kg/m^3)	Water absorption (%)	Particle gradation					
				Sieve size (mm)	40	20	10	5	Bottom
10–20	2498	1312	0.79	Residue (%)	–	66.8	33.0	0.1	0.1
5–10	2688	1403	1.14	Residue (%)	–	–	51.5	46	2.5

Table 4
Mix proportions of concrete specimens.

ID	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water reducer (%)	Air entrain agent (%)
A	340	142.8	643	1256	1	/
B	340	142.8	597	1237	0.5	0.01
C	340	142.8	590	1222	0.4	0.02
D	340	142.8	583	1220	0.3	0.03

Note: The water reducer and AEA are percentage of the cement content.

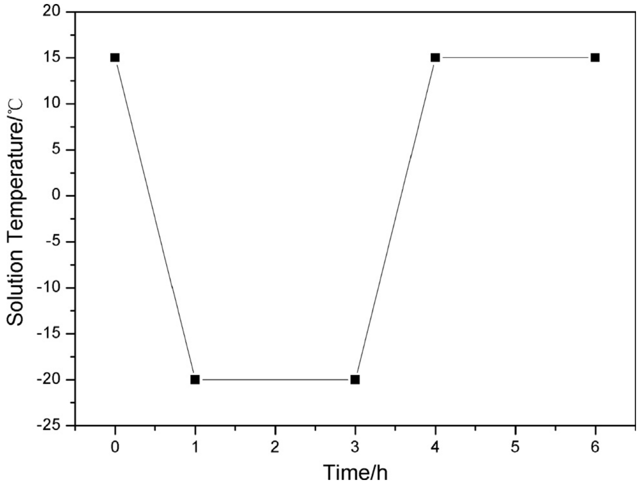

Fig. 1. Temperature setting of freeze-thaw cycles.

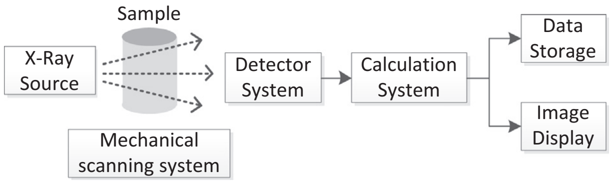

Fig. 2. Schematic illustration of the operation of high precision computerized tomography system.

frost damage [11,12], but findings from Wang et al. is not in coincidence with the air contents as the standards regulated, which means that the restriction of air content is inadequate [14]. Adding AEA can significantly increases the number of air voids in the range between 20 and 200 μm for air-entrained mortars [15], and Zhang et al. [16] found that hardened cement paste with an intermediate pore size between 40 and 200 nm exhibited poor frost resistance due to high capillary force. Hence it can be seen that of air voids distribution should be considered as well for enhancing the frost resistance of concrete.

Currently, Mercury intrusion porosimetry (MIP) and image analysis are commonly used technologies for measuring the air voids for cementious materials, and the two methods have non-ignorable limitations. The pretreatment such as drying and polishing are needed for image analysis method, since scanning electron microscopy (SEM) and optical microscopy (OM) only provide the information of cutting face of the specimens. The pretreatment will cause damage to samples in turn, which brings difference between the observed microstructure and actual constitutes of concrete [17,18]. The assumption of MIP method is that pores are cylindrical and entirely accessible to mercury, but the existence of “ink-bottle” pores is the inherent limitation that cannot be neglected [19,20]. Moreover, excessive mercury injection pressure can cause collapse of the pore structure, and the sample cannot be used for additional measurement [21].

Computerized tomography (CT) is a non-destructive testing technology that was originally applied in medicine area. A concrete cylinder with diameter of 150 mm was scanned by medical CT in 1980, but only the aggregates, steel bars and cracks were observed because of the limitation to resolution of 1 mm/voxel [22]. With the development of computer technology and materials science, the industrial CT with higher radiation energy and stronger penetrating ability was invented. Burlion et al. [23] studied the variation of pores and interfacial transition zone (ITZ) under the chemical attack by industrial CT, and observed the increase of pore

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