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Fractal analysis of effect of air void on freeze–thaw resistance of concrete

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HIGHLIGHTS

- A fractal model was built to characterize the air voids size-distribution.
- The fractal model was validated more reliable than previous model.
- The air voids size-distribution showed significant influence on frost resistance.
- A regression model between fractal dimension and durability factor was obtained.

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ABSTRACT

Pore structure is one of the major characteristics influencing the freeze–thaw resistance of concrete. Although the air-void spacing factor associated to the porosity features of concrete is known as a widely used parameter to assess the freeze–thaw resistance, controversies on the determination of critical values of air-void spacing factor still exist in many related studies. Moreover, it is reported that the pore-size distribution in concrete also significantly affects its freeze–thaw resistance. In this study, a fractal model was established to characterize the air voids size-distribution in concrete, and the corresponding fractal dimension obtained from the fractal model was validated for its effectiveness in describing the air voids size-distribution quantitatively. By comparison to a fractal model presented in a previous study, the fractal model proposed in this study was found more reasonable and reliable. Based on the theoretical principle, correlations between air voids size-distributions and the measured freeze–thaw resistances of concrete were established through laboratory experiments. The results revealed that air voids size-distribution exhibited more significant influence on the freeze–thaw resistance of concrete than the air-void spacing. Furthermore, a regression equation with fairly high correlation coefficient between the fractal dimension of air voids size-distribution and the durability factors of concrete was obtained from the results.

1. Introduction

Due to the pore structure of concrete, freezing and thawing is one of the major reasons leading to its deterioration or failure. Based on the hypothesis of hydrostatic pressure proposed by Powers [1], a direct relationship can be found between the freeze–thaw resistance and the air-void spacing of concrete, and the spacing factor of air voids is proposed to be less than 250 μm to obtain the adequate freeze–thaw resistance for the concrete. Numerous researches have been reported on the relationship between the freeze–thaw resistance and the spacing factor in recent decades [2–6]. Although the significance of the influence of spacing factor on the freeze–thaw resistance is illustrated in many studies, there are still some controversies on the determination of critical values of the spacing factor (i.e. the maximum air-void spacing over which frost damage occurs under given conditions) among the conclusions. For example, Pigeon and Malhotra [4] conducted the freeze–thaw test and air-void test on roller compacted concrete. The research results indicate that the critical spacing factor of 250 μm is not necessary for obtaining the adequate freeze–thaw resistance. This conclusion was also validated by Gao et al. [5] through experiments. For another example, the research conducted by Zhang et al. [6] shows that the critical spacing factor is related to the strength grade of concrete, and the higher strength grade corresponds to the greater critical spacing factor. In order to find a better indirect method to evaluate the freeze–thaw resistance, many other parameters associated with the characteristics of pore structure, such as the pore volume, flow length, median pore diameter and shape of pore have been utilized to characterize the freeze–thaw resistance of concrete [7–10]. The effects of

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pore-size distribution were also taken into account in many studies. By building a 3D modeling for the pore structure of concrete, a series studies reported by Nakamura et al. demonstrate that pore-size distribution of concrete has significant effects on its freeze–thaw resistance [11–13]. Thus, the pore-size distribution has become a focusing aspect in the study on the assessment of freeze–thaw resistance with pore structure. However, the lack of quantitative parameter for the size distribution of pore structure has always been a bottleneck for the related studies. As a crucial characteristic of the pore structure, the size distributions of air voids need to be considered more accurately for a better micro-characterization of the freeze–thaw resistance of concrete.

Currently, it is difficult to characterize the distribution of air voids quantitatively through common approaches due to the complexity of the pore structure of concrete. Some literatures [14–18] indicate that the pore structure of concrete can be considered as a fractal object in which the fractal characteristics of pore shapes, pore surface areas and pore volumes are distinct. As a new branch of nonlinear science, fractal geometry is generally applied to describe a chaotic system which is invariant under certain transformation scales. This invariance is called self-similarity. Apart from self-similarity, another property of fractal objects is non-integer dimension, which is defined as fractal dimension. Generally, a chaotic system can be characterized through a fractal dimension, which is defined as an intermediate dimension between the Euclidean dimensions, as a consequence of the complexity of the system [19]. Therefore, the complexity and heterogeneity of the air-void structure of concrete can be described through a fractal dimension. In other words, if a proper fractal model is built, a fractal dimension can be obtained from that model to characterize the air-void structure effectively and quantitatively.

Hu [18] proposed that the complexity and heterogeneity of the air-void structure in concrete can be characterized by a fractal dimension, which was defined as the fractal dimension of pore-size distribution. Through a linear regression analysis between the number of air voids larger than a certain size and the diameter of air voids, the fractal dimension of pore-size distribution can be calculated as the slope of the best fitting linear equation. However, the data in Hu's study [18] indicates that the relationship between the number and the diameter of air voids is apparently nonlinear, which indicates that the fractal model used by Hu [18] may not be suitable for characterizing the air voids size-distribution. Hence, in order to better assess the freeze–thaw resistance based on the pore structure of concrete, an improved and more reliable fractal model is required to address the fractal characteristics of the air voids size-distribution more effectively and accurately.

2. Objectives and scope

The primary objectives of this study are to develop an effective fractal model for characterizing the size-distribution of air voids in concrete and evaluate the influence of the size-distribution of air voids on the freeze–thaw resistance of concrete based on the proposed fractal model. Air-void analyzing tests were considered on 8 Portland cement concrete mixtures to obtain the diameters and the number of air voids for the establishment of the fractal model, and durability factors were achieved through the freezing and thawing tests performed on the same concrete mixtures.

3. Methodology

The box-counting dimension, also known as the Minkowski–Bouligand dimension, is one of the dimensions most commonly applied to fractals. Let F be any non-empty bounded subset of R^n, and $N_\delta(F)$ be the smallest number of the boxes with an equal size δ that covers F [20]. The box-counting dimension can be expressed as [20]:

$$D = \lim_{\delta \to 0} \frac{\lg N_\delta(F)}{\lg(1/\delta)} \tag{1}$$

In the definition of the box-counting dimension, the boxes used to cover the fractal object can be either squares or circles in a plane, or spheres or cubes in a three-dimensional space. Those boxes can be either overlapped or non-overlapped with each other [20]. The shapes and positions of the boxes in box-counting dimension are so flexible that it is convenient to implement the box-counting dimension on a particular practical application. Generally, the air voids in the concrete can be regarded as interconnected spheres, so the shapes of the air voids on a plane section tend to be circular. According to these characteristics, the box-counting dimension with a circular shaped box was adopted in this study for the development of a fractal model to characterize the size-distribution of air voids in concrete.

4. Laboratory experiment

4.1. Materials

Ordinary Type I/II Portland cement was selected for the concrete mixtures. Ground granulated blast-furnace slag (GGBS) (2.80 g/cm^3 in density and 410 m^2/kg in specific surface area), fly ash (FA) (4.4% in fineness), silica fume (SF) (2.1 g/cm^3 in density, 24,100 m^2/kg in specific surface area, and 95.8% in SiO_2 content) were used as partial replacements for cement. Fine aggregate was a mixture of natural sand and manufactured sand with a ratio of 4:6. The fineness module of fine aggregate was 2.85, and the fines content was 1.1%. Crushed limestone was used as the coarse aggregate with 5–25 mm in particle sizes, 0.3% in fines content and 0.5% in water absorption. Naphthalene sulfonate water-reducing admixture and rosin-based air-entraining agent were used as additives.

4.2. Mix proportions

Five groups of non-air-entrained and three groups of air-entrained concrete were considered in this study. The mix proportions are presented in Tables 1 and 2. In Table 1, GGBS, FA and SF represent the mixtures in which the cement was partially replaced by GGBS, fly ash and silica fume at certain ratios, respectively. In the compound mixture, the cementitious material consisted of cement, GGBS, fly ash as well as silica fume. In Table 2, A1, A2 and A3 represent the concrete mixtures modified by different percentages of air-entrained agent by the weight of cement. During the preparation of concrete, the slumps of all the mixtures were controlled at 10 ± 3 cm.

Table 1
Mix proportions for ordinary concrete (kg/m^3).

Mixture	Cement	Fine aggregate	Coarse aggregate	Water	Silica fume	Fly ash	GGBS
Control	400	613	1138	200	–	–	–
GGBS	260	613	1138	200	–	–	140
FA	280	613	1138	200	–	120	–
SF	360	613	1138	200	40	–	–
Compound	280	613	1138	200	20	40	60

Table 2
Mix proportions for air-entrained concrete (kg/m^3).

Mixture	Cement	Fine aggregate	Coarse aggregate	Water	Air-entrained agent, ‰	Air content in fresh concrete, %
A1	400	613	1138	200	0.09	2.6
A2	400	613	1138	200	0.15	5.5
A3	400	613	1138	200	0.35	7.0