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Fractal analysis of relation between strength and pore structure of hardened mortar

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HIGHLIGHTS

- A mathematical relation between strength and pore structure is addressed.
- The pore volume and pore size distribution are considered in the strength model.
- Capillary pore volume and fractal dimension are representative parameters.
- Fractal dimension is an accurate parameter to quantify the pore size distribution.
- Fractal model use in this study is validated more reliable than common used.

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ABSTRACT

The pore structure is the fatal factor which influences the strength of cement mortar and concrete. A lot of researches on the relationship between the strength and the pore structure were developed. Initially, porosity is the only factor in the strength models. As the development of research, it is illustrated that the pore size distribution also has significant effect on the strength. The pore size distribution is taken into consideration in the strength model in different forms. However, these models are still unavailable to simulate the relationship between strength and pore structure, because the parameters used for representing the pore size distribution are not accurate enough. In the present research, strength and pore structure were tested on thirteen Portland cement mortar mixtures to collect the original data of the strength and pore structure. In order to enhance the reliability of the strength model, the pore volume and the pore size distribution were all considered. The fractal theory was employed to characterize the pore size distribution more accurately than ever used parameters. According to the regression analysis results, the fractal dimension of pore surface and the capillary pore volume were respectively selected as representative parameters of pore size distribution and pore volume. The research results indicate that the relations between strength and fractal dimension and capillary pore volume present positive power function and negative power function respectively. The ratio of fractal dimension to capillary pore volume is addressed as the new parameter for strength model. Finally, relational expression of power function is proposed between the compressive strength and the ratio of fractal dimension to capillary pore volume. Regression analysis indicates that the strength model relative to pore structure addressed in this study has high prediction accuracy.

1. Introduction

It is recognized that the strength of mortar and concrete depends on its pore structure. A lot of researches on the relationship between the strength and the pore structure were developed. Initially, porosity is the only factor considered in the strength models of cement-based materials established by many researchers [1–11]. However, the experimental results show that these strength models are not accurate enough for strength prediction, because not only the porosity but also the pore size distribution has vital influence on the strength. Consequently, many researchers devoted their time to digging the relations between the strength and the pore size distribution through different methods [12–18]. In these researches, the sectioned porosities and the mean distribution

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radius are proposed to describe the pore size distribution. These parameters promote the strength models comparing to the models only with porosity, but the models are still not accurate enough for strength prediction. The parameters of pore structure used in these models are still over general, so seeking valid parameters to quantify the pore size distribution is the key point. In all, in order to obtain the quantitative relation between strength and pore structure reliably, the pore volume and pore size distribution should be both considered. Moreover, it is significant to find a valid method to describe the pore size distribution quantitatively and accurately.

Currently, the pore size distribution is difficult to be characterized quantitatively with common approaches due to the complexity and irregularity of the pore structure. The literatures [19–22] have indicated that the pore structure of concrete and mortar can be considered as a fractal object in aspect of pore surface areas, pore volumes, pore shapes, etc. As a new nonlinear science, the fractal geometry is generally applied to describe a chaotic system which is called fractal objects. The self-similarity is an important feature of fractal objects which means that each piece of the fractal objects is geometrically similar to the whole. In addition, although the fractal object is a chaotic system, it can be characterized through a stationary *non-integer dimension* between the Euclidean dimensions, which is defined as the fractal dimension. Non-integer dimension is the other feature of fractal objects. The fractal dimension is the quantitative parameter to describe the degree of irregularity of the fractal objects [23]. Therefore, if a proper fractal model is obtained, a fractal dimension can be calculated from the model to characterize the complexity and irregularity of the pore structure effectively and quantitatively.

The complexity and irregularity of the pore structure presents as the pore size distribution. Different kinds of fractal models were attempted to quantify the pore size distribution, such as space-filling model, Menger sponge model, pore axis fractal model, fractal model of pore cross-section contour, etc [19,21,22,24]. The fractal dimensions of pore volume, pore surface area and pore axis are calculated by these models. Some studies were also addressed on the relationship between the mechanical property, durability and fractal dimension. However, most of these fractal models are all borrowed from other research areas without considering characteristic and test method of pore structure, which lead to low accuracy and reliability of fractal model on the analysis of the pore size distribution. Among these fractal models, Menger sponge model is the most common model for pore structure in the past researches, which is also borrowed from other area. MIP (Mercury Intrusion Porosimetry) data of pore structure is put into Menger sponge model to calculate the fractal dimension of pore surface area directly. Actually, the progress of Menger sponge modeling and MIP test are different. In other words, the Menger sponge model is not suitable to simulate the pore structure, which results in low accuracy of calculated fractal dimension inevitably. Inaccurate fractal dimensions also lower the reliability of relation analysis between strength and pore structure.

Hence, in order to obtain a better mathematical model relating strength to pore structure of mortar, a more reliable fractal model is required to describe the characteristics of the pore size-distribution more effectively and accurately.

2. Object and scope

The primary objectives of this study are to develop a mathematical model relating the strength to the pore structure of mortar, which may be useful for predicting the strength of mortar with different proportions at different ages. The tests of the strength and the pore structure were performed on thirteen Portland cement mortar mixtures. The mercury intrusion porosimeter (MIP) was employed to obtain the data of pore structure. The influences of pore volume and pore size distribution on the strength were all considered for establishing the mathematical model. The fractal theory was used to quantify the pore size distribution.

3. Laboratory experiment

3.1. Material

The cement used for the mortar mixtures is Ordinary Type I/II Portland. Ground granulated blast-furnace slag (GGBS), fly ash (FA), silica fume (SF) are selected as partial replacements for cement to create the different pore structure in mortar. The parameters of above admixtures are list in Table 1. Naphthalene sulfonate is used as water-reducing agent. Fine aggregate is mixed by natural and manufactured sand at a ratio of 4:6 to make the fineness modulus meet the standard of medium sand which is generally used for cement mortar and concrete. The fineness modulus and the mud content is 2.85 and 1.1% respectively.

3.2. Proportion of mixtures

Thirteen groups of mortar were considered in this study. The mix proportions are presented in Table 2. As shown, FA, GGBS and SF represent the mortar in which the cement is respectively replaced by FA, GGBS and SF at certain ratios; C1, C2 and C3 represent the compound mixtures in which the cementitious material is composed of cement, GGBS, FA and SF.

3.3. Test method

3.3.1. Strength

Strength tests were conducted according to the "Standard Test Method for Strength of Cement Mortar (T0506-2005)" in the Chinese Standard Specification of "Test Methods of Cement and Concrete for Highway Engineering (JTG E30-2005)" [25]. This testing protocol is the same as the method specified in the ISO 679 [26]. The size of specimens for strength testing is $40 \times 40 \times 160$ mm. Triplicate specimens were tested for each mortar mixture. Prior to testing, all the specimens were cured in the curing room at a temperature of 20 ± 2 °C and a relative humidity no less than 95% for 3 days, 7 days, 28 days and 56 days. Bending strength was conducted first on each specimen. Two half specimens from bending strength test were used for compressive strength. The compression area for compressive strength test is 40×40 mm^2.

3.3.2. Pore structure

The mercury intrusion porometers (MIP) was employed to investigate the pore structure of the hardened mortar. The size of specimens for MIP test is 3–5 mm. In order to keep consistency of data source, the specimens for MIP are particles of the mortar which were crushed from the specimens for strength tests. The range of the pore diameter measured in this study is 3–360,000 nm.

4. Methodology

In order to develop an accurate quantitative parameter for the pore size distribution, the fractal theory was adopted. Literature review stated in the section of 'Introduction' indicates although Menger sponge model [24] is the most common fractal model in existing researches on pore structure of cement mortar and concrete, the calculated results indicate that this model is not accurate and stable enough for characterizing the pore size distribution of