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Fractal dimension in concrete and implementation for meso-simulation

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HIGHLIGHTS

- Define and clarify the fractal dimensions of aggregates and cement.
- Form a mathematical model to describe the geometrical characteristics of concrete.
- Analyze and compare the meso-models generated by the RFM and TGM.
- The concrete samples with the same fractal dimension are very similar.

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ABSTRACT

A complete understanding of the geometrical structure of concrete is important. Based on the geometrical characteristics of concrete, hypothesizing that graded aggregates have a fractal effect is reasonable. In the framework of fractal theory, the fractal dimensions of aggregates and cement were clarified, and a mathematical model of the fractal dimension was formed to describe the geometrical characteristics of concrete. Two numerical meso-model groups generated by the random fractal and traditional generation method were measured and analyzed considering the gradation curve, coarse aggregate content, and weighted mean size as evaluation indices. It was verified that the evaluation indices of the numerical models with the fractal dimension of actual concrete and those of actual concrete were the same, and the numerical simulation results were consistent with theory. Based on sampling statistical analysis, the geometrical homogenization of the meso-model generated by the random fractal method was found to be satisfactory for meso-scale applications.

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1. Introduction

As a widely used building material, concrete plays an indispensable role in engineering construction. The safety of concrete structures and the economy of design and construction have a significant impact on society and the environment. Therefore, the study of the mechanical properties of concrete material should be combined with recent research findings in the fields of physics, mechanics, materials, and information in an effort to more scientifically describe the failure of materials and more accurately simulate and predict the mechanical behavior. As a useful complement to experimental science, numerical simulation could be used to develop precise design and control in engineering structures; additionally, it could reduce security risks and economic investment.

In the 1980s, symbolized by the concept of numerical concrete (le béton numérique) [1], the meso-mechanics of concrete was established. As concrete meso-mechanics was being applied and promoted, some marked changes occurred in the field of the study on concrete mechanical behavior. Wittmann, the founder of concrete meso-mechanics, considers that the internal structure of concrete could be studied on three different scales, i.e., macro-scale (10^{-1} m to 10^{-3} m), meso-scale (10^{-4} m to 10^{-1} m), and micro-scale (10^{-8} m to 10^{-4} m). The mechanical behavior of a scale could be explained by the structural characters in the finer scale [2]. For example, in the meso-scale, concrete could be considered a mixture of aggregate, cement, and the interface between these two materials. The properties and the interaction of these three compositions could have a direct impact on the macro-properties of concrete.

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As meso-scale theory could help researchers to more profoundly understand the failure process and mechanical properties of concrete in the macro-scale [3], meso-mechanics has become the primary interest and focus in the field of concrete research. meso-scale theory has been used to study concrete creep [4], failure of concrete under a dynamic load [5], the theory of kinematics enhancement [6], and the size effect [7].

There are two main ways to study in the framework of this theory: experimentation and numerical simulation. Experimentation is used to measure the mechanical properties of material and verify the results of meso-scale simulations. For instance, Gu et al. [8] introduced a method to measure the mechanical properties of the interface between aggregates and mortar in concrete; Huang et al. [9]verified the application of meso-scale fracture model by using X-ray computed tomography (CT); Ren et al. [10] established a method for observing the fracture pattern. Wang et al. [11] established a three-dimensional (3-D) reconstruction method based on CT. Numerical simulations have the advantages of having no experimental condition restrictions and more convenient and accurate data collection. With the rapid improvements to computer hardware, this methodology is constantly improving. There are two types of meso-scale numerical models for concrete: the finite element method and the discrete element method [12]. The finite element method is solved based on the mechanics of continuous media. The discrete element method can solve problems that have displacements with unconformity.

In the research process, some problems have attracted special attention; namely, in addition to materials properties, the spatial distribution of aggregates has an impact on several properties in macro-scale such as concrete carbonation [13], creep [14], and the failure behavior of polyurethane polymer concrete [15]. However, the analyses on these phenomena have yet to fully elucidate their processes. It might be argued that there is no appropriate mathematical model to describe and define the complex geometrical properties of concrete. Specifically, in the framework of meso-mechanics, a differential equation model is formed to calculate the stress and strain in concrete by considering concrete as a three-phase mixture, using the homogenization theory of solid mechanics, and factoring the interactions between aggregates and cement. In addition to the material properties, the spatial distribution of aggregates should be described quantitatively in the differential equations model. However, classical geometry cannot solve the problem because of the irregularity of the aggregates' shape and collection. Presently, the spatial properties are described using probabilistic methods [16].

Fractal geometry—established by Mandelbrot [17]—is usually used to solve problems with irregular and fragmented patterns that cannot be treated with classical geometry. With the help of fractal theory, researchers could connect the geometric forms, spatial properties, and mechanical behaviors of the objects; thus, the mechanical behaviors of the objects could be analyzed effectively. Some researchers have made great contributions to the application of fractal geometry in the field of complex materials and mechanics. Most research is conducted on the geometry pattern such as measurement and analysis of the boundary of concrete carbonation [18] and analysis and simplification of the fracture surface [19].

Meanwhile, some researchers have started using fractal theory to generate the concrete aggregate meso-model [20]. In general, the methods for concrete meso-modeling can be classified into three categories. In the first category—the traditional generation model (TGM)—random aggregate models are generated and then allocated in the concrete model sequentially [21]. The second category includes methods that provide simultaneous generation and allocation [22]. In the third category, the locations and boundaries of the aggregates are determined before generating the aggregates, e.g., the method introduced in [23].

Each of the aforementioned generation methods has advantages and disadvantages; for example, methods in the first category are relatively complicated, but it provides more accurate modeling. In contrast, methods in the second category reduce computational burdens, but they often generate irregularly shaped aggregate models and fail to accurately represent the gradation of actual conditions [24]. Likewise, methods in the third category also save computational time, but they provide a lower coarse aggregate content. The Random Fractal Method (RFM) is a modified method that belongs to the third category, the boundaries of around an aggregate are defined simultaneously with the generation of the aggregate.

In this paper, the geometrical properties of aggregate distribution are analyzed. The main works in the paper are as follows. First, the geometrical properties of aggregates and cement are analyzed quantitatively on the basis of fractal theory—the fractal dimension is selected as an index to describe the status of the concrete; a mathematical model that can describe the geometrical characteristics is formed. Then, a group of numerical models is generated, and the result of the application is verified by comparing with existing experiments and by using sampling statistical analysis.

2. Method

2.1. Principal hypotheses and assumptions

To establish a systematic and complete theory system, and simplify simulating methods, three basic hypotheses are introduced in this paper:

Hypothesis 1. *The set of aggregates and cement is as a fractal.*

Hypothesis 2. *All the aggregates are simulated as convex.*

Hypothesis 3. *There is always a space between any two aggregates.*

More details with respect to these hypotheses and some corollaries are given below.

Based on Hypothesis 1, the theories within the framework of fractal geometry could be applied. In particular, some conclusions relevant this study are presented.

Corollary 1. *Any part selected from concrete is fractal, where the set of aggregates and the set of cement have the same fractal dimension as the original concrete.*

Based on this corollary, the simulated model could be reduced wantonly in shape; simultaneously, the geometric properties and the fractal dimension could remain constant.

Corollary 2. *One approach to fractal geometry is to regard two sets as 'the same' if there is a bi-Lipschitz mapping between them.*

In the theory of fractal geometry, the Hausdorff dimension is invariant under bi-Lipschitz transformations, which is set up to distinguish between sets that are not homeomorphic. Therefore, if two sets have the same Hausdorff dimension, these two sets could be considered the same.

Corollary 3. *The fractal dimension mentioned could be considered as the Hausdorff dimension or the box-counting dimension.*

However, the mathematical meaning of the Hausdorff dimension is different from that of the box-counting dimension, and each has its advantages and disadvantages. The Box-counting dimension

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