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Concrete meso-structure characteristics and mechanical property research with numerical methods

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HIGHLIGHTS

- Fractal theory is introduced as a representative index of concrete meso-structure.
- The average fractal dimension increases with the size increases.
- The whole fractal dimension decreases with the size increases.
- Maximum bearing capacity rises with aggregate volume fraction and specimen size.
- Nominal strength rises with aggregate volume, but declines with specimen size.

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ABSTRACT

Concrete meso-structure significantly affects its mechanical property, as crack generally starts and develops basically along the interface between aggregate and mortar on the meso-scale. The cracking path is highly dependent on the interface structure, the main component of concrete meso-structure. Since the interface is formed due to aggregate distributing in mortar mix, the relation between aggregate surface area and interface perimeter could be considered as a representative index of concrete meso-structure. As it is too complicated to adopt traditional methods to represent this relation, in order to better understanding the influence of meso-structure change on mechanical property, fractal theory is introduced to explore the relationship, with the main focus on the characteristics of the concrete meso-structure and its influence on mechanical property. Results show that the specimen size has great impact on meso-structure and mechanical property, while the influence of aggregate volume fraction can be neglected. It is more obvious in larger specimen size that aggregate volume fraction increase could contribute a lot to bearing capacity improving and whole stress level descending. Besides, aggregate volume fraction increase could improve the local cracking stress, but reduce the cracking strain, resulting in cracking brittleness.

1. Introduction

Aggregate, mortar and the interface formed between them are the main components of concrete in meso-scale, and they have a great influence on concrete macroscopic mechanical properties. The development of meso-mechanics theory and methods enable the researchers to study concrete on meso-scale. There are mainly two ways to establish concrete meso-structure model, the digital imaging method based on CT scanning and image processing [1–3] and numerical methods for generating aggregate [4–6]. Although, the former method could establish real concrete meso-structure, it costs too much and the quality of generated concrete meso-model is affected by the image processing method [3,6]. The latter method is simple, feasible, and repeatable with less cost. The generated concrete models are mostly with aggregate shape of circular, elliptical and arbitrary polygon, which are referred as numerical concrete models [6–9]. Unger and Wriggers focused on the generating methods of the aggregate shape of circular, elliptical and arbitrary polygonal, and presented the generating method and strategy [5,6,9,10]. It should be pointed that the aggregate sizes need to meet the requirements of the Fuller sieve analysis [6,10,11] (i.e. grading requirements), in order to control the aggregate surface area and particle size of concrete specimens. Due to

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the low generated volume fraction of the circular and elliptical aggregate model in practical operation [6,10], the method of generating arbitrary polygon is put forward [8,9,12]. Three dimensional (3-D) concrete specimens with high aggregate volume fraction could be similar to real concrete. According to the geometric area equivalent principle of aggregate section, a more realistic and efficient aggregate generating and delivering method is brought up [9,13].

Using numerical concrete model, lots of researchers [4,9,14–18] focus on the study of concrete cracking, deformation and other mechanical properties. It is pointed out [19,20] that different aggregate shape of concrete specimen has little effect on its mechanical property, while the interface, the weakest part in the meso-structure, has great influence on its meso-structure and mechanical property. The aggregate proportion of a specimen is an important factor to its mechanical property, and the interface structure is the main factor that affects the cracking [21]. Unger and Du [1,5] stated that the micro cracks initiate basically in the interface between aggregate and mortar, and tend to converge and coalesce to form a macroscopic crack in the position of close aggregate particles. When a macroscopic crack formed, no more macroscopic crack would be formed. The crack propagation path in concrete is not regular, but basically along the interface between aggregate and mortar. Carpinteri [22–24] also made some progresses on the crack initiation and propagation by the theory of micro-mechanics. The interface structure, formed by the distribution of aggregate in the mortar matrix, has a certain relation between the shape and volume fraction of aggregate. The interface structure changes with the aggregate volume fraction and specimen size, which can be considered as a representative index of the meso-structure. Therefore, in order to research the meso-structure characteristics, the relation between the aggregate surface area and interface perimeter would be the key issue. In order to study the concrete property from microscopic to macroscopic scale, the method of lineation [18] is used to simulate and simplify the interface between aggregate and mortar based on this relationship. It simplifies the original model from three phases to two, greatly reduces the time of the finite element calculation. Therefore, it is valuable and significantly practical to start with the relation of aggregate surface area and interface perimeter to study the change low of meso-structure.

Actually, the difference of aggregate shape and its randomness will cause the interface perimeter change, even with the same specimen size and aggregate volume fraction. Interface is the weak area, where micro-cracks tend to initiate and converge, and has great influence on macro-crack formation and development. Therefore, it is necessary to employ modern mathematical method to analyze the characteristics change of concrete meso-structure, and its influence on mechanical property. The interface perimeter will change with the shape and surface area of aggregate, resulting in the change of concrete meso-structure. Thus, the meso-structure of concrete specimen can be characterized by the relation between aggregate surface area and interface perimeter. This problem could be solved with fractal theory and method [25], which aims at studying irregular or non-smooth nonlinear problem, and is adopted here to characterize and quantify the irregularity. Fractal method has been widely applied in concrete research field, such as crack, fracture etc. [26,27]. Many researchers have considered the existence of the fractal effect in the graded aggregates, by taking the installation, formation and construction of concrete into account [28,29].

In this paper, fractal theory is introduced to quantify the relation between aggregate surface area and interface perimeter, aiming to (1) study the change characteristics of this relation, and (2) its influence on concrete specimen mechanical property.

2. Methods and materials

2.1. Fractal theory

Fractal theory is still not mature and lack of unified approach, therefore, the method chosen generally depends on the actual situation. Common-used methods are box dimension, similar dimension, capacity dimension, and area-perimeter. The method of area-perimeter is applied in this study to quantify the representative index of the relation between aggregate surface area and interface perimeter, including perimeter-measurement and area-measurement. In a two-dimensional numerical concrete specimen, the aggregate volume fraction can be controlled, but the interface perimeter is uncertain. Therefore, the fractal method used is perimeter-measurement method.

The perimeter-measurement method is the filling degree measure of the object perimeter in a plane area, usually used in determining the fractal dimension of the interface perimeter. It is calculated through the relation between the perimeter and the area. The expression is $P = kA^{\frac{D}{2}}$, where D is the average or total fractal dimension of perimeter of a single island or islands; P is the interface perimeter; A is the surface area; and K is scale constant. The fractal dimension can be obtained by taking logarithmic transformation of the formula above to obtain $\log P = \log k + \frac{D}{2} \log A$. According to this formula, it is possible to obtain the corresponding fractal dimension (D) and constant of scale (k) from the perimeter and area by linear fitting analysis.

2.2. Meso-aggregate model of concrete

Five meso-scopic concrete specimens are obtained using the 2D-RAS generating method [9]. The load-deflection curves of the specimens (Fig. 1) show that the simulated results agree well with the test results, verifying the reliability of generation method for meso-structure research. As the geometric area of aggregate section in the two-dimensional concrete specimen is equivalent to the aggregate volume fraction in three-dimension, the two dimensional (2-D) grading curve could be derived from the Fuller curve of 3-D. Based on probability and statistics theory, Walraven [30] converted the three-dimensional grading curve to the probability of the aggregate diameter D < D_0 at any point in the specimen section, which is widely applied, as

$$P_c(D < D_0) = P_k \times \Big[1.065(D_0/D_{\max})^{1/2} - 0.053(D_0/D_{\max})^4 - 0.012(D_0/D_{\max})^6 - 0.0045(D_0/D_{\max})^8 + 0.0025(D_0/D_{\max})^{10}\Big]$$

where, D_{max} is the minimum size of aggregate particles, P_k is the percentage of aggregate volume that accounts for the total volume of concrete, usually $P_k = 0.75$.

Schutter [31] compares the results of the model based on the above equation with the actual concrete cross section by means of image analysis. It shows that the calculated 2-D grading curve meet the mix ratio of the actual concrete well. Therefore, the 2-D concrete specimen model can be adopted to study the relation of aggregate surface area and interface perimeter on its meso-structure.

Sixteen three-grade concrete of specimens are obtained with the 2D-RAS method (Fig. 2). The aggregate volume fractions are 40%, 45%, 50%, and 55%, specimen sizes are 200 × 200 mm^2, 300 × 300 mm^2, 400 × 400 mm^2 and 500 × 500 mm^2, respectively. The generated aggregate diameter is between 5 and 80 mm.

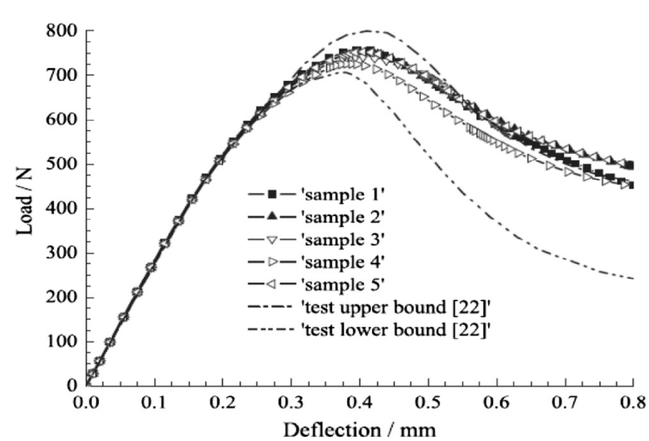

Fig. 1. Load-deflection response for meso-aggregate specimens.