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Morphological characterization and mechanical analysis for coarse aggregate skeleton of asphalt mixture based on discrete-element modeling

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HIGHLIGHTS

- Morphological characteristics of coarse aggregates were quantified.
- Morphology of coarse aggregates were reconstructed within PFC2D.
- Virtual penetration test was built to predict mechanical property of aggregates.
- Stronger aggregate skeleton leads to better penetration resistance.

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ABSTRACT

Focused on the aggregate microstructures to characterize the aggregate mechanical properties, this paper proposed a modeling method of coarse aggregate based on the particle morphological characteristics. By using the Aggregate Image Measurement System (AIMS), the realistic shape of granular aggregates was captured and the statistical analysis was made to quantify the morphological differences firstly. Then by using Discrete-Element Method (DEM) software named as Particle Flow Code in two dimensions (PFC2D) and with the help of the image processing techniques, an algorithm was developed to model the two-dimensional shape of aggregates. Through linking the shape to the morphological index for each aggregate, the coarse aggregate skeleton was built which is consistent with the actual composition and structure of the laboratory specimens. After that, based on laboratory penetration test for granular aggregates, virtual penetration test was built by PFC2D to verify the validity of the developed modeling algorithm. An optimized method was proposed further then to improve the simulation efficiency. This is because of the time-consuming process when modeling the actual specimen which was composed of numerous coarse aggregates with various shapes. Some representative particles were selected and reconstructed based on the angularity index to form the virtual specimens with aggregates of gradations AC-13 and SMA-13. At last the virtual penetration test of AC-13, SMA-13 was conducted to predict the mechanical behavior and the coarse aggregate skeleton structure characteristics were analyzed from the point of micro-contact state. It is proved that the proposed modeling algorithm could well capture the realistic shape of aggregates and virtual test based on the aggregates model could characterize the granular aggregates mechanical properties accurately.

1. Introduction

The Discrete-Element Method is widely used in simulating the mechanical behavior of the granular materials nowadays [1–3]. During discrete-element modeling, the precision of numerical model and property prediction highly rely on the size and number of discrete elements [4–6]. However, limited by the current computer storage capacity and computing speed, numerous discrete elements during virtual modeling and tests could be very time-consumed. Therefore, due to the difficulties in balancing the precision of simulation and the computation efficiency, most of the existing methods tend to simplify the realistic shape of the granular materials during the modeling process. Although some researchers proposed methods to build the virtual shape consistent with the actual materials, it could not quantify the morphological

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characteristics of each particle when simulating as well. All of these lead to the inaccuracy of the DEM simulation in Road Engineering nowadays.

The realistic shape of granular materials is considerable and will influence the structure and mechanical behavior of mixture to some extent, including void content, elasticity modulus, rutting, fatigue cracking and so on [7–14]. Test conducted by Janoo [9] showed that the volume of void in the aggregates was found to increase with increasing aggregate angularity. Rocco and Elices [10] investigated the shape effect of aggregate on the concrete and concluded that concrete made with crushed aggregates provided values of the elasticity modulus higher than concrete made with spherical ones. And there was a tendency for the modulus to decrease with aggregate size for both kinds of aggregates. Bessa et al. [11] pointed out that aggregate shape properties, such as form, angularity, and surface texture, highly influenced the performance of hot-mix asphalt. Rutting is related to aggregate angularity and fatigue cracking can be decreased by an aggregate rough surface texture. Similar findings were also shown by Sengoz [12] that a relationship existed between the shape characteristics of aggregates and the surface properties of HMA. According to the published data above, it is important to take the realistic particle shape into consideration when use the Discrete-Element Method. Many modeling methods have been proposed that fall into two general categories [15]. One is the stochastic algorithm and another utilizes some scanning devices.

The stochastic algorithm controls the modeling process by some random conditions. Lu and McDowell [16] proposed an algorithm to model the ballast particle using overlapping balls. In this algorithm, a ball was first created at the center of a cubic cell as the main body of the particle and then other balls could be created along fourteen directions around the center ball. Zhang [17] regarded the aggregate particles as hexahedrons, pentahedrons and tetrahedrons. First it generated large amount of balls in order to fill the sample area. 3 random numbers which represented the X, Y, Z coordinate values respectively were used to control the main side lengths of each particle. This process cuts the whole sample area into many particle areas and void areas. Then the balls inside the particle area were convert into a clump. The particles generated by these stochastic algorithms are simplified to some extent but can develop samples quickly with large amount. The shape of particle is random, not accurate and the morphological characteristics cannot be quantified. Such methods are similar to the study of the Liu [18] and Tutumluer [19] as well.

The X-ray tomography imaging and other scanning technology were successfully used to reconstruct the particles by some researchers [20–23]. These means can model the particle shape precisely but was not able to quantify the morphological characteristics same as the stochastic algorithm. Because the X-ray tomography imaging technology only provides the scanning images without measuring any related morphological characteristics. To quantify the morphological characteristics of aggregates, many researchers have proposed methods or adopted some other apparatus. The Sobel-Feldman operation were adopted to quantify aggregate angularity using the gradient approach in the research conducted by Chen et al. [24]. And the Sobel-Feldman operation was improved further by Yang et al. [25] to measure the three-dimensional surface of aggregates instead of two-dimensional characteristics. Apparatus is utilized to measure the morphological characteristics of aggregates such as CPA (Computerized Particle Analysis) [26], Princeton gamma-tech (PGT) image analysis system [27], University of Illinois Aggregate Image Analyzer (UIAIA) [28], the Fourier Transform Interferometry (FTI) [29–30] and the Aggregate Image Measurement System (AIMS) [31–34].

The objective of this study is to propose a method to build the virtual particle capturing the realistic shape and linking the morphological characteristics to each particle. The AIMS equipment was used to measure and quantify the morphological characteristics of coarse aggregates. A commercial DEM software named Particle Flow Code in two dimensions (PFC2D) was used to build micromechanical modeling of coarse aggregate skeleton and conducted virtual penetration test. The coarse aggregate skeleton structure characteristics were analyzed from the point of micro-contact state based on the virtual penetration test to indicate the mechanical properties of coarse aggregates.

The rest of this paper is organized as follows. Section 2 mainly introduces the experimental materials, apparatus and the basis micromechanical models adopted in the research process. In Section 3, the modeling methods to reconstruct the particles and specimen are proposed. Section 4 analyzes the differences of various particles based on the morphological characteristics. Then virtual penetration tests are carried out to verify the validity of the developed modeling methods and the micro-analysis on aggregate skeleton is conducted to predict the mechanical behavior. Finally, some research findings are summarized in Section 5.

2. Experimental and methodology

2.1. Materials

The basalt coarse aggregates were divided into various size particles through standard sieve as the following particle diameters: 4.75–9.5 mm, 9.5–13.2 mm, 13.2–19 mm, 19–26.5 mm. The 4.75 mm aggregates were called for short to represent the particles with a diameter distribution between 4.75 and 9.5 mm. The other size aggregates were the same. To improve the scanning accuracy, the sieved coarse aggregates were washed and dried to keep the particle surface clean without obvious dust. 7 kinds of aggregate specimen were prepared as the following different combinations. And the gradations of the SMA-13, AC-13 are shown in Table 1.

(1) 4.75, 9.5, 13.2, 16, 19 mm coarse aggregate specimen;
(2) 70% 4.75 mm+30% 19 mm coarse aggregate specimen;
(3) 70% 9.5 mm+30% 19 mm coarse aggregate specimen;
(4) 70% 13.2 mm+30% 19 mm coarse aggregate specimen;
(5) 70% 16 mm+30% 19 mm coarse aggregate specimen;
(6) SMA-13 coarse aggregate specimen;
(7) AC-13 coarse aggregate specimen.

2.2. Laboratory test

Penetration test [35] by using Universal Testing Machine (UTM) was designed to characterize the inner frictional resistance of coarse aggregate. 7 kinds of coarse aggregates were prepared according to the Section 2.1 and then were put into a cylindrical mould. The cylindrical mould is 12 cm high and its diameter is 15 cm. Fig. 1 shows the cylindrical mould used in the penetration test. The coarse aggregates were put in the mould in three times. Then a tamping bar was used to hit the specimen surface each time after the coarse aggregates put into make the specimen compacted. During penetration test, a cylindrical penetration rod was penetrated into the testing sample at a speed of 1.27 mm/min. The diameter of the loading head is 50 mm. The penetration resistance along with the penetration depth was recorded.

The Aggregate Image Measurement System (AIMS) was utilized to capture the coarse aggregate realistic shape. The aggregate images will be captured by the high resolution camera and the morphological characteristics based on the images will be calculated by the inner software including angularity index, texture index, dimensional value and so on, as following equations [31].

(1) Angularity index

$$GA = \frac{1}{\frac{n}{s} - 1} \sum_{i=1}^{n-3} |\theta_i - \theta_{i+3}| \quad (1)$$

where, θ angle of orientation of the edge points; n is the total number of points; subscript i denoting the ith point on the edge of the particle.

(2) Texture index

$$TX = \frac{1}{3N} \sum_{i=1}^{3} \sum_{j=1}^{N} (D_{i,j}(x,y))^2 \quad (2)$$

where, D = decomposition function; n = decomposition level; N = total number of coefficients in an image; i = 1,2, or 3 for detailed images; j = wavelet index; x, y = location of the coefficients in transformed domain.