Construction and Building Materials 102 (2016) 843–851

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Verification and application of two-dimensional slice identification method in three-dimensional mesostructure under different aggregate gradations and packing algorithms

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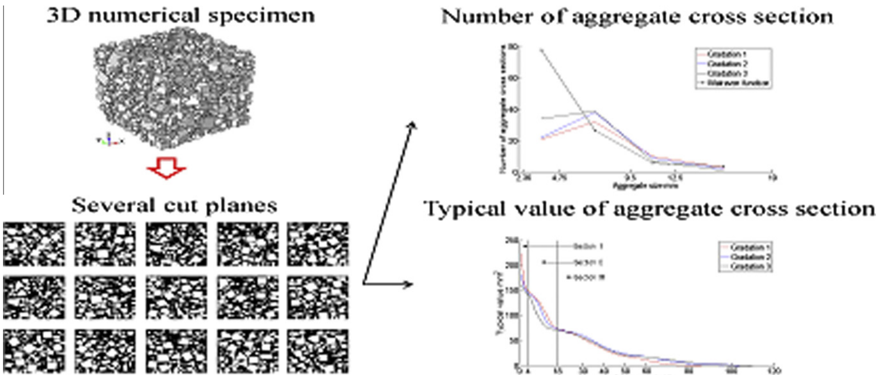
HIGHLIGHTS

- An improved aggregate packing algorithm is valuable for 3D numerical specimens.
- 2D slice identification method is valid under different aggregate gradations.
- Walraven function is appropriate for asphalt specimens based on Fuller's Curve.
- A special section of aggregate cross section areas can judge aggregate gradations.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 April 2015
Received in revised form 16 October 2015
Accepted 1 November 2015
Available online 18 November 2015

Keywords:
Concrete
Mesostructure
Image identification
Aggregate packing algorithm
Three-dimensional numerical specimen
Two-dimensional slice identification

ABSTRACT

The aim of this paper is to build more reasonable three-dimensional (3D) mesostructure numerical specimens and to study relationships between 3D mesostructure numerical specimens and their two-dimensional (2D) slices using an improved algorithm called Embedded-Zoom Aggregate Algorithm. According to experiments used by Walraven, equivalent 3D numerical specimens containing cube aggregates were built. All cut planes parallel to each surface of above specimens were identified respectively to count the number of different aggregate cross section areas. Comparison results between 2D identification method and Walraven function can prove the consistency of 2D identification method. For asphalt concrete, by analyzing 2D slice identification method, Walraven function and real specimen cut planes, results of the first two methods are both similar to the last one. Grading curves in ASTM were selected to further judge the applicability of Walraven function and 2D identification method. Results indicated that Walraven function is unsuitable for ASTM. Meanwhile, a relationship between an aggregate gradation and a special section of aggregate cross section areas under descending spectrum in cut planes was found by 2D slice identification method. Embedded-Zoom Aggregate Algorithm presented in this paper is proved to be valid. Moreover, the average area of aggregate cross sections in a special section can effectively distinguish various 3D grading curves.

1. Introduction

Nowadays, concrete mesomechanics, whose characteristic scale usually lies between nanometer and millimeter, is gradually

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http://dx.doi.org/10.1016/j.conbuildmat.2015.11.002
0950-0618/

studied by more and more scholars. With the progress of computer techniques, simulations of concrete mesostructure specimen develop. Many common methods appear to predict the concrete performance, including Finite Element Method (FEM) [1–6], Discrete Element Method (DEM) [7–9], Meso-Element Equivalent Method (MEEM) [10], Cohesive Zone Modeling (CZM) [11–13], Lattice Model (LM) [14] and so on. Among these methods, although 2D numerical specimens are inaccurate to simulate material characteristics, they can be used to simplify 3D numerical specimens in many conditions, so they are still worth studying. What's more, an accurate 3D numerical specimen modeling is difficult to be simulated, because it costs many resources for computer storage and operation.

Before modeling a numerical specimen, a packing algorithm is needed. Aggregate shapes of simulations were initially considered as circles (2D) or spheres (3D) [14–16]. Until now, circle algorithm and sphere algorithm are still being used because of their simple operation. For example, bituminous composites' complex moduli in 2D and 3D numerical models are studied [17]. Commonly, Monte Carlo simulations are used at the same time [1]. On the base of sphere aggregates, 3D aggregate shapes evolve into simple convex geometries. For instance, by varying sizes of ellipsoidal particles, four distinctive shapes ranging from spheres to elongated and disc shaped particles can be obtained to study the effect of aggregate shape on diffusivity, and it is found that shapes and orientations of aggregate particles have significant effects on diffusivity [18]. By controlling sizes and locations of sphere aggregates, tetrahedral or hexahedral fundamental aggregates are generated based on sphere aggregates [19]. This method, defined as Embedded Algorithm in this paper, is similar to embed the convex geometry into a sphere. Whatever aggregate shapes, the difficulty in 3D aggregate placement lies in overlapping check. For sphere aggregates, an efficient way to achieve overlapping check is to compare the distance using two sphere aggregates' centroid coordinates and the sum of their radius. Aggregates are projected into regular lattices, so collision and overlapping detection is translated into a straightforward exercise of finding out whether two particles occupy the same site, rather than having to compute and test intersections between any two particles, which is usually very expensive for non-spherical particles [20].

Aggregate shapes and gradations are usually studied with the help of image recognition and analysis technology. X-ray computed tomography (X-ray CT) is commonly used to obtain cut planes. 2D images are often transformed into equivalent binary images, which are clearly distinguished by segmentation and denoising operation. For instance, X-ray CT is used to compare 2D and 3D image-based aggregate morphological indices [21]. By identifying a quantitative method to characterize the 3D mesostructure of the matrix in asphalt mixture, coarse aggregate shows most influence on the direction of anisotropy of the asphalt mastic [22]. X-ray CT is also used to scan dense-graded asphalt concrete (DGA) to obtain slices and planar images [23,24], from which the 3D microstructure is reconstructed [23–25]. Using a combination of different methods of core cylinder images from the pavement to obtain a reliable gradation of the mineral skeleton of the mixture is possible [26].

Numerical modeling methods develop from 2D to 3D, and aggregate shapes vary from simple geometries to complex convex polyhedrons gradually. More factors, which can make a numerical specimen more real, are considered to form a multi-phase system. The method of 3D aggregate placement mainly contains two difficulties: (a) storage of aggregate edges and corners. All information occupies much RAM when the number of aggregates is abundant. (b) Overlapping check. While aggregates have complex shapes, it is difficult to place them in the numerical specimen without intersection.

Background grid method is an effective overlapping check method in a FE model. This paper presents Embedded-Zoom Aggregate Algorithm which is based on both sphere aggregate algorithm and background grid method. This algorithm, which adopts background grid method to achieve aggregate overlapping check, can raise the volume fraction of placed aggregates by adjusting aggregate sizes in a small range. Referring to experiments used by Walraven [27], Embedded-Zoom Aggregate Algorithm is used to establish 3D numerical specimens. 2D cut planes, whose planar images are identified to figure out the number of different aggregate cross sections, are obtained by slicing 3D numerical specimens. Applicability of Walraven function is verified according to identified numbers of aggregate cross sections in 2D cut planes. Furthermore, gradations of 3D numerical specimens can be distinguished by 2D identification method in corresponding cut planes.

2. Three dimensional numerical specimen modeling

2.1. Embedded-Zoom Aggregate Algorithm

Overlapping check is easy for 3D sphere aggregate packing algorithm. Another common algorithm (Embedded Algorithm) places an embedded aggregate in a sphere, whose basic idea is to select several correlate points randomly on the sphere surface. These points, which can generate edges and surfaces of a new aggregate, are chosen as vertices. Under the circumstance of placing spheres successfully, Embedded Algorithm can avoid the check step for aggregate overlapping. The disadvantage of this approach is sparse aggregate placement, small volume fraction and low strength for numerical specimens. This paper, which takes some improvement on Embedded Algorithm, uses Embedded-Zoom Aggregate Algorithm to generate cube aggregates. By applying background grid method in the algorithm, cube aggregate sizes can be adjusted to avoid intersections with each other, which alter disadvantages mentioned above. Main steps of Embedded-Zoom Aggregate Algorithm are performed as follows:

2.1.1. Centroid determination from sphere aggregate generation

Edges of a numerical specimen are confirmed in a 3D Cartesian coordinate system where positions of all specimen surfaces are determined. A vertex of the specimen shares the same position with the origin. Sphere aggregates ascertained in different gradations, which will be thrown in the numerical specimen, decrease progressively according to their diameters. With Monte Carlo method, centroid coordinates of sphere aggregates are created one by one randomly according to the diameter order within the limits of the specimen.

2.1.2. Grid property of finite element model

A FE model of the numerical specimen meshed equidistantly has same size elements, which are classified as a motar element set before placing aggregates.

2.1.3. Generation of cube aggregates and first aggregate placement

Sorted by volume in descending order, sphere aggregate diameters extracted from the numerical specimen are used to compute cube aggregate sizes based on volume equivalent principle. Generated cube aggregates use same centroid coordinates created by sphere aggregates with equal volumes. The first cube aggregate, which will be thrown in the numerical specimen, is rotated around its centroid randomly in three axes. Coordinates of eight vertices of the cube aggregate are calculated to confirm its final location. Through position overlapping judgment between the cube aggregate profile and equal size elements meshed in the FE model, over-