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Image-aided random aggregate packing for computational modeling of asphalt concrete microstructure

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HIGHLIGHTS

- Generate microstructure of asphalt mixture using image-aided aggregate packing and volumetrics.
- Validate robustness and consistency of developed algorithm for random generation.
- Predict dynamic modulus of asphalt mixture as compared to experimental measurements.

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ABSTRACT

Computational modeling is an effective tool to study complex microstructure of stone-based infrastructure material such as asphalt concrete (AC). In this paper, a hybrid approach of image scanning and aggregate packing is developed to randomly generate two-dimension digital specimens of asphalt concrete for virtual testing. Detailed shape characteristics of aggregates are captured using the calibrated high-resolution images. The virtual microstructure is generated based on Random Sequential Addition (RSA) packing after knowing volumetric composition of AC. The microstructure was used for virtual testing of AC using finite element modeling (FEM). Dynamic modulus testing was simulated and the predicted results were validated with laboratory testing results reported in the literature. The robustness and consistency of the packing method were proved by generating different digital specimens with random selection and placement of aggregates having the same gradation. The effect of shape variation of aggregates due to random selection and spatial distribution was found negligible for dynamic modulus predicted from the virtual testing. The discrepancies between simulated and measured results were discussed for future improvements of virtual testing of AC using computational modeling.

1. Introduction

Asphalt Concrete (AC) is the one of the most important civil materials for paving highways. Laboratory testing protocols are extensively used by transportation agencies to determine AC properties and link to field performance of asphalt pavements. For example, dynamic modulus testing is conducted at different loading frequencies and temperatures to capture viscoelastic behavior of AC that affects stress and strain distribution in the pavement under vehicular and thermal loading [1]. The laboratory testing procedures require specimen preparation and equipment calibration, which are labor intensive, time consuming, and expensive. In addition, experienced technicians and repetitive specimens are usually needed to avoid random and systematic errors.

An alternative way for physical laboratory tests would be computer simulations. As the fast development of computer technology, computational modelling based on numerical analysis methods such as finite element method (FEM) and discrete element method (DEM) has been extensively used by researchers to study the composite behavior of AC. The flexibility of computational methods allows consideration of complex material properties of material constituents and heterogeneous microstructure of composite asphalt mixture. With the necessary of experimental validation, computational modeling can eliminate the need for large amounts of lab tests and generate the satisfactory results in a more cost-effective way.

It is crucial to properly define a computational model that it can represent physical testing of AC using digital specimens. The digital specimen needs to satisfy two criteria. The first one is the correct constitutive relationships and material properties of the constituents of AC. The second criterion is the geometrical representation of composite components across different length

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scales. For an ideal case, the constituents of AC (aggregate, asphalt binder, and air void) need to be represented separately, which is possible from geometrical point of view but requires significant costs computationally.

To be able to model the aggregates with different sizes and the binder matrix in a more practical and cost-effective way, the concept of fine aggregate matrix (FAM) has been proposed by the researchers. In this concept the AC microstructure is usually assumed to have two separate phases including coarse aggregates and the FAM phase that includes fine aggregates, mineral filler, and asphalt binder. In this case, air void may be assumed as part of the FAM phase or as a separate phase in the mixture. This assumption requires that the properties of the FAM phase to be determined separately as a homogeneous sample. This is usually achieved by conducting dynamic shear modulus test or uniaxial tension–compression test on small cylindrical bar specimens of FAM, on which frequency-sweep test is performed to obtain viscoelastic properties [2,3].

Different approaches of generating microstructure of AC have been practiced in the literature, in which assumptions vary from simple shapes such as circles and ellipsoids for aggregates to more realistic aggregate shapes. These methods can be categorized into two categories based on the generating procedures: (1) generating a digital assembly based on a physical fabricated AC specimen through image scanning, (2) using random aggregate shape generating and distributing algorithms.

The first category of microstructure generation is based on two-dimensional (2-D) or three-dimensional images of AC physical specimens. Although 2-D images are easy to be taken, it is considered as a destructive method as the specimen needs to be cut for taking multiple images [4–7]. Thus the same AC specimen cannot be used for lab testing and comparison of results with the digital specimen. Computed Tomography (CT) X-ray technique has been evolved recently for study of asphalt mixture as a non-destructive method [8–13]. The three-dimensional (3-D) digital specimens are generated by stacking up scanned 2-D sections of an AC specimen captured at a specified interval to reconstruct the tomography of 3-D microstructure. A post-processing process is needed to link the scanned 2-D sections and separate FAM and coarse aggregate phases. Although CT can generate digital specimens with satisfactory microstructure characteristics of AC mixture, this method is very time consuming and the specialized X-ray equipment is needed. The accuracy of CT scans to capture the shape of coarse aggregates in the AC depends on the sampling rate and resolution of X-ray beam.

The second category of microstructure generation is using mathematical algorithms to produce a random assembly of aggregates with specific shapes and then distribute aggregates into the continuous phase of FAM [14–18]. This makes it convenient to include statistical patterns of the volumetrics of AC mixture and the properties of FAM source. The variations could exist in aggregate gradation, binder content, air void content, and shape characteristics of aggregates such as form and angularity. In the previous researches on random generation of microstructure, n-edged polygons were usually used as the representation of aggregate shape. The placement of aggregates in the FAM is achieved through "take and place" approach in the 2-D model. In this case, the maximum fraction of aggregate area may be limited due to tedious trials in the placement process.

To achieve the satisfactory agreement between the shape characteristics of the virtually generated particles and the actual aggregates used in AC, the packing algorithm for random generation and placement of aggregate particles should be capable of capturing the morphological properties of individual aggregates and their distribution patterns in the digital specimen. The major challenges include the use of automatic control method for aggregate overlap prevention while consistently satisfying the geometrical limitations of aggregate shapes and the maximum limit of aggregate fraction that can be reached in the assembly during the packing process. The ideal case would be randomly generating 3-D microstructures with the individual aggregates (from CT scans or reconstruction of 2-D images). In this case, physical specimens of AC are not needed but 3-D feature of microstructure is still kept. However, the challenge of dense packing aggregates in the 3-D domain exists due to the irregular shape of aggregate. Therefore, this study focused on digital testing using the randomly generated 2-D models as the first step.

2. Objectives

The objective of this study is to develop a computational microstructural model using a hybrid approach of image scanning and random generation. The microstructure model can be used to study mechanical properties of AC considering actual shape properties of aggregates. To achieve this objective, an innovative algorithm is developed to generate 2-D virtual microstructure of AC using aggregate image inventory and circle packing method. The virtual microstructure is able to generate digital specimens based on volumetric properties of AC without the need of using the cross-section cut of physical specimen for imaging. Dynamic modulus testing was simulated to demonstrate the successful validation and applicability of the virtual microstructure. The discrepancies between the simulated and measured results were discussed for future improvements of virtual laboratory testing of AC using computational modeling.

3. Generation of virtual microstructure

3.1. Framework of image-aided microstructure generation

An image-aided random generation method is developed for generating virtual microstructure that directly uses the 2-D images of the actual aggregate and circle packing algorithm. Compared to the purely random microstructure with artificial aggregate shapes, one significant advantage of the hybrid (image-aided random distribution) method is that the shape characteristics of coarse aggregates are automatically satisfied if the aggregate image inventory has the minimum required number of aggregate samples for each sieve size in a statistical sense.

The microstructure of virtual specimen is generated according to the two-phase model assumption comprising coarse aggregates and FAM. This assumption is commonly used for microstructure modeling of asphalt mixture in the literature [6,18]. The coarse aggregates include the aggregates retaining on the sieve size of 1.18 mm, while the FAM phase is assumed to be homogenous that is the mixture of asphalt binder, filler, and fine aggregates.

As shown in the Fig. 1, the framework of virtual microstructure generation includes the following steps:

1- Digital images are taken for aggregates at each sieve size to build the image inventory.
2- For each gradation size, a number of aggregates are chosen from the image inventory and analyzed through a developed algorithm to obtain the shape and geometrical properties of aggregate.
3- The volumetric properties and domain dimension are introduced to the algorithm as inputs of the assembly generation process.
4- To generate the microstructure assembly, the aggregates is placed randomly in the desired domain area without overlaps while achieving the required gradation of coarse aggregate (it is equivalent to the area of aggregate in 2D).