Applied Thermal Engineering 84 (2015) 368–374

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Evaluation of thermal conductivity of asphalt concrete with heterogeneous microstructure

Jiaqi Chen [a, b], Miao Zhang [a], Hao Wang [b, *], Liang Li [a]

[a] Dept. of Civil Engineering, Central South University, Changsha, Hunan 410075, China
[b] Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854, USA

HIGHLIGHTS

- Generate three-dimensional microstructure of asphalt concrete with three-phases.
- Simulate steady heat transfer to predict thermal conductivity of asphalt concrete.
- Validate finite-element simulation results with experimental data.
- Evaluate effects of aggregate characteristics, conductive filler, and specimen sizes.

ARTICLE INFO

Article history:
Received 19 January 2015
Accepted 30 March 2015
Available online 7 April 2015

Keywords:
Asphalt concrete
Thermal conductivity
Random aggregate microstructure
Finite element analysis
Thermal modification

ABSTRACT

Thermal conductivity of asphalt concrete determines the temperature distribution in asphalt pavements and thus affects viscoelastic modulus of asphalt concrete and the microclimate environment near pavement surface. This paper developed an innovative model to evaluate thermal conductivity of asphalt concrete with heterogeneous microstructure. The three-dimensional (3-D) microstructures of asphalt concrete was simulated with different-sized aggregates and air voids randomly distributed in asphalt binder. A hierarchical multi-scale finite element (FE) modeling approach was used to simulate the steady heat transfer process for predicting the effective thermal conductivity of asphalt concrete. The results were validated with experiment data reported in the literature. With the developed model, the effects of aspect ratios and orientation angles of aggregate, conductive filler, and specimen size on thermal conductivity of asphalt concrete were analyzed. Results show that the orientation angle and aspect ratio of aggregate have combined effects on thermal conductivity of asphalt concrete, depending on the orientation of the longest diagonal of aggregate with respect to the direction of heat conduction. The thermal conductivity of asphalt concrete is affected by the content and shape of graphite filler for thermal modification. On the other hand, it is recommended that the specimen size should be at least five times the maximum aggregate size for measuring thermal conductivity. The larger ratio of specimen size to maximum aggregate size is needed when the maximum aggregate size increases. In general, the developed model can be used as an analysis tool to guide the mix design of asphalt concrete for thermal optimization.

1. Introduction

Asphalt concrete is one of the most widely used pavement materials in road construction. Thermal properties of asphalt concrete have important influences on temperature distributions in the asphalt pavement structure and thus pavement life [1]. Due to viscoelastic nature of asphalt binder, mechanical properties of asphalt concrete vary significantly due to diurnal and seasonal temperature changes that affect the stresses and strains in the asphalt pavement caused by vehicular and thermal loading [2]. In addition, pavement surface temperature affects the near-surface air temperature that contributes to the Urban Heat Island (UHI) effect [3].

Thermal properties of asphalt concrete have been mainly studied through experiments. Cote et al. [4] measured the thermal conductivity of asphalt concrete considering the influence of air void and aggregate. Islam and Tarefder [5] determined thermal properties of asphalt concrete using laboratory testing and finite element. The results were validated using field data. Recently, interests have been generated to modify thermal properties of

* Corresponding author.
E-mail address: hwang.cee@rutgers.edu (H. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2015.03.070

asphalt concrete for different applications. Zhou et al. [6] measured the thermal conductivity of asphalt binder modified by graphite and cenosphere for increased thermal conduction or insulation. Dawson et al. [7] added different additives such as cooper slag and cooper fibers into asphalt concrete for heat storage and transfer applications. In order to reduce the temperature in the pavement at summer, Feng et al. [8] replaced the traditional aggregates in asphalt concrete with low-conductivity ceramic particles for the pavement surface layer. Pan et al. [9] measured the specific heat, thermal conductivity, and diffusivity of asphalt binder modified with graphite, and investigated the anti-aging properties. Although the experiment method provides a direct and simple way to measure thermal properties of asphalt concrete, it has some inherent limitations. In order to avoid the variation in experimental measurements, a number of physical samples should be prepared and tested, which increases testing time and economic costs. The thermal conductivity of asphalt concrete is affected by its volumetric parameters and thermal properties of each component. If an analytical model is available to predict the effective thermal conductivity of asphalt concrete based on its microstructure, experiment costs can be significantly saved. Analytical models have been developed to predict thermal conductivity of composite material based on the thermal conductivity and volume fraction of each component, such as the parallel model, the series model, and the Maxwell–Eucken model, and the Effective Medium Theory (EMT) method [10–13]. However, since these models usually assume two phases with simple distribution patterns, which are different from the heterogeneous microstructure of the real asphalt concrete, the existing models may not be directly used for predicting thermal conductivity of asphalt concrete. In order to accurately predict the composite behavior of asphalt concrete, microscopic models have been developed to simulate the internal microstructure of asphalt concrete. These microstructure-based models have been extensively used in the evaluation of mechanical properties of asphalt concrete, such as dynamic modulus, creep stiffness, and fracture energy [14–17]. However, few models have been developed to investigate thermal properties of asphalt concrete considering the aggregate microstructure and volumetric compositions. The microscopic study on thermal properties of asphalt concrete would be of great meaning to guide the mix design of asphalt concrete for thermal optimization based on volumetric parameters and thermal properties of each component.

2. Objective

The objective of this paper is to evaluate the effective thermal conductivity of asphalt concrete with heterogeneous microstructure. A multi-scale 3-D microstructure model of asphalt concrete was randomly generated and imported into finite element (FE) analysis. Various parameters were considered in the three-phase microstructure model, such as volume fractions and spatial distributions of mixture components, including asphalt binder, aggregate, and air voids. Experimental data from previous researches were used to validate the model results. Sensitivity analysis was conducted to investigate the effects of aggregate characteristics, conductive filler, and specimen sizes on the effective thermal conductivity of asphalt concrete.

3. Prediction of effective thermal conductivity

3.1. Microstructure of asphalt concrete

In this paper, asphalt concrete was modeled as a three-phase heterogeneous material with asphalt binder, aggregate, and air voids. An innovative 3-D microstructure generation algorithm was developed in which aggregates and air voids were represented by simplified polyhedrons distributed in the asphalt binder. The generation process of 3-D microstructure of asphalt concrete can be summarized as follows:

(1) Randomly generate a set of points with polar angles and polar radius in the polar coordinate system. Then connect these points sequentially to form a random polygon, which represents for the cross section of an aggregate.
(2) Calculate the major axis and minor axis of the polygon. Then scale the minor axis to obtain the expected aspect ratio. In this step, the major axis is defined as the longest diagonal of the polygon, while the minor axis is defined as the longest length in the direction perpendicular to the polygon major axis. The aspect ratio is defined as the ratio between the major axis and the minor axis.
(3) Scale the polygon until the size of the polygon falls into two adjoining sieve sizes as specified in the gradation of asphalt concrete. Then randomly assign an orientation angle to the polygon by rotating the polygon. The orientation angle is defined as the angle between the polygon major axis and the horizontal direction.
(4) Stretch the above 2-D polygon to a random length and form a 3-D polyhedron. In order to ensure the aggregate size and its major axis unchanged, the stretched length should be not greater than the length of major axis and satisfying the sieving size criteria that the aggregate could pass. The stretched length is also controlled to avoid generating the flaky-shape aggregate.
(5) Randomly place the generated 3-D polyhedron into a prescribed 3-D rectangular space, which represents the asphalt concrete sample. If any edge of the polyhedron overlaps with any existing polyhedron, a new position should be arranged to the polyhedron randomly, until there is no overlap between polyhedrons.
(6) Repeat step 1 to step 5, until the total volume of the generated polyhedron is equal to the prescribed volume of the aggregates.
(7) Generate and place air voids. The generation algorithm of air voids is similar with that of aggregates. When the air voids are placed in the sample, the region within the sample boundary excluding aggregates and air voids is asphalt.

A set of MATLAB codes were developed to implement the above processes. An asphalt sample generated with the 3-D microstructure is shown in Fig. 1. For a single aggregate, the 3-D polyhedron was obtained by stretching the 2-D polygon into the third dimension with the same cross section. However, the model is capable to simulate the orientation of each individual aggregate in the cubic specimen.

3.2. Development of FE model

With the developed microstructure of asphalt concrete, FE analysis was conducted to calculate the effective thermal conductivity. The developed FE model considers a steady heat transfer process as shown in Fig. 2.

The constant temperatures T_1 and T_2 were applied to the top and bottom boundaries of the cubic sample respectively. Heat insulation condition was applied to the other four boundaries of the cubic sample. The only material parameters needed in the FE simulation are thermal conductivity values of asphalt binder and aggregates. The thermal flux in the y-direction is generated due to the temperature difference between T1 and T2. It is noted that the calculate results will not change with the temperature difference