Construction and Building Materials 77 (2015) 187–196

Contents lists available at ScienceDirect

Construction and Building Materials

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

Study of the internal mechanical response of an asphalt mixture by 3-D discrete element modeling

Huan Feng [a,*], Matteo Pettinari [a], Bernhard Hofko [b], Henrik Stang [a]

[a] DTU, Department of Civil Engineering, Brovej 118, Kgs. Lyngby 2800, Denmark
[b] Institute of Transportation – Research Center for Road Engineering, Vienna University of Technology, Gusshausstraße 28/230/3, 1040 Vienna, Austria

HIGHLIGHTS

- The viscoelastic behavior of asphalt mixture was studied by a 3D DEM model.
- Constant set of Burger's parameters calibrated with laboratory test data.
- The ball density may affect the simulation results.
- The internal stresses distribution under dynamic loading have been investigated.

ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form 11 December 2014
Accepted 12 December 2014
Available online 10 January 2015

Keywords:
Asphalt mixtures
Viscoelastic
Discrete element method
Micromechanical modeling
Burger's model
Frequency–temperature superposition

ABSTRACT

In this paper the viscoelastic behavior of asphalt mixture was investigated by employing a three-dimensional Discrete Element Method (DEM). The cylinder model was filled with cubic array of spheres with a specified radius, and was considered as a whole mixture with uniform contact properties for all the distinct elements. The dynamic modulus and phase angle from uniaxial complex modulus tests of the asphalt mixtures in the laboratory have been collected. A macro-scale Burger's model was first established and the input parameters of Burger's contact model were calibrated by fitting with the lab test data of the complex modulus of the asphalt mixture. The Burger's contact model parameters are usually calibrated for each frequency. While in this research a constant set of Burger's parameters has been calibrated and used for all the test frequencies, the calibration procedure and the reliability of which have been validated. The dynamic modulus of asphalt mixtures were predicted by conducting Discrete Element simulation under dynamic strain control loading. In order to reduce the calculation time, a method based on frequency–temperature superposition principle has been implemented. The ball density effect on the internal stress distribution of the asphalt mixture model has been studied when using this method. Furthermore, the internal stresses under dynamic loading have been studied. The agreement between the predicted and the laboratory test results of the complex modulus shows the reliability of DEM for capturing the viscoelastic properties of asphalt mixtures.

1. Introduction

Asphalt mixture is a complex system that comprises different materials, including mastic, aggregate and air void, in which the mastic phase exhibits viscoelastic behavior in pavement service conditions. One of the most challenging tasks for pavement engineers is a realistic prediction of asphalt pavement performance, which is dependent on the material properties, the environmental and loading conditions. From the material properties point of view, asphalt mixture's individual components and the way they interact with each other play a significant role in the asphalt mixtures performance.

Due to the difficulties and consumption of measuring, experimental testing is not always the most attractive strategy to study asphalt mixture at micro-scale level. While, numerical simulation based on fundamental material mechanics and theories has the advantage of being able to access the impact of individual material component on the performance of asphalt mixture, and is comparatively more convenient and economical to implement. Discrete element method is one type of numerical simulation method which allows the finite displacement and rotation of discrete particles. Especially after combined with Burger's model, Discrete

* Corresponding author.
E-mail addresses: hufe@byg.dtu.dk (H. Feng), matpe@byg.dtu.dk (M. Pettinari), bernhard.hofko@tuwien.ac.at (B. Hofko), hs@byg.dtu.dk (H. Stang).

http://dx.doi.org/10.1016/j.conbuildmat.2014.12.022
0950-0618/

Element Method (DEM) could be used as an excellent tool to capture the viscoelastic behavior of asphalt mixture. The commercial software Particle Flow Code 3D (*PFC*^{3D}) developed by Itasca consulting group has been used in this study.

When it comes to simulating asphalt mixtures with DEM, there are mainly two issues that concern pavement researchers: the aggregate shape and different contact models. First, in order to take into account of the aggregate shape effects, different strategies have been developed. Dondi et al. [1] studied the effect of shape and interlocking of grains on the packing characteristics of the aggregate particles in asphalt mix. The aggregate shape effect was considered by using spheres with different diameters. The degree of aggregate contact and interlocking are found to be a function of grain shape and angularity. Liu et al. [2] developed an algorithm, which could randomly generate irregular polyhedron particles to represent the coarse aggregates. One drawback of this method is the big amount of spheres used will significantly increase the calculation time. By using the advanced imaging techniques, Khattak et al. [3] developed a 2D micro-mechanical discrete element model for hot mix asphalt (HMA) mixtures. The specimen was first scanned to obtain a digital image of the cross-sectional area. Then a black and white digital image was generated that would interpret matrix and aggregate phases, respectively. The digital image was processed to establish a numerical logical matrix of the digital image identifying aggregate and matrix pixels. Yu et al. [4] studied the effect of aggregate size distribution and angularity distribution on dynamic modulus using a 3D discrete element method (DEM). Angular particles are generated using an image-based ball-clumping approach which requires significantly reduced number of balls and is capable of capturing the particle shape and angularity effect. The same approach has been adopted by Chen et al. [5]. In Adhikari's study [6], the microstructure of the asphalt concrete specimen was captured by X-ray tomography techniques. The hollow circular images were produced from the layer of cylindrical X-ray computed tomography (X-ray CT) images. The asphalt concrete images were divided into three phases according to a density index: aggregate, sand mastic and air void phases. This approach could be time-consuming and requires large computational resources despite of its accuracy.

Compared to the codes that model continua, *PFC*^{3D} works at a more basic level: it 'synthesizes' material behavior from the micro-components that make up the material [7]. In DEM simulation, different materials can be distinguished by assigning different interactions between particles, which is usually called contact models. However, it is difficult to choose such properties so that they could represent the real material, which brought the second main issue with DEM modeling. In order to capture the viscoelastic behavior of asphalt mastic, Burger's model has been introduced in DEM simulation. Liu et al. [8] developed a viscoelastic model of asphalt mixtures with the discrete element method. The relationship between the microscale model input and macroscale material properties was derived, and an iterative procedure was developed to fit the dynamic modulus test data of asphalt mastic with Burger's model, in which the Maxwell model stiffness and damping were initialized first and kept constant, and then the Kelvin model's stiffness and damping were calibrated for each frequency. The same way of calibrating Burger's model was also adopted by Chen et al. [9] and Yu et al. [10]. By using Burger's model, Dondi et al. [11] studied the DSR complex shear modulus of asphalt binder using 3D discrete element approach. The model has been proved to be able to predict complex modulus and the phase angle of the studied polymer modified bitumen over a wide range of temperatures and frequencies. You et al. [12] studied asphalt concrete subjected to haversine loading. Viscoelastic parameters for the Burger's model were calibrated from uniaxial dynamic modulus testing results of asphalt sand mastic, while the Discrete Element (DE) prediction was verified by comparing with the experimental testing results of asphalt. Another difficulty related to the contact models is big amount of design parameters, which usually could not be derived directly from lab data. Effort has been devoted to the study of different design parameters by many researchers. For example, Cai et al. [13] studied the effects of the normal to shear contact stiffness ratio on the bulk properties, the parallel bond radius, the number of particles and their positions. Especially, the nine design parameters of Burger's model have been further investigated in his work.

In summary, existing studies provided meaningful insights into understanding and simulating the dynamic properties of asphalt mixtures with DEM. In this paper, a different method has been developed for calibrating the Burger's model: a constant set of Burger's model parameters, which were obtained by fitting the laboratory test data from the whole testing frequency range, has been used for all the frequencies. In addition, when using the time–temperature superposition principle, the ball density effect on the internal stress distribution of the asphalt mixture model has been further investigated.

2. Objectives and scopes

In order to study the viscoelastic behavior of asphalt mixture based on a three-dimensional discrete element model, the research was carried out in two phases. In the first phase, the laboratory tests were performed and complex modulus of asphalt mixtures has been collected. The model was considered as a whole mixture with uniform contact properties for all the distinct elements. Therefore, the input parameters for the Burger's model were calibrated based on the laboratory test results of the whole asphalt mixture, instead of just the mastic phase which provides the viscoelasticity for the asphalt mixture. A constant set of Burger's model was calibrated for all the loading frequencies, which is different compared to the traditional way of calibration where the Burger's model parameters were calibrated for each loading frequency [8–10]. One of the main objectives of this research is to validate the calibration procedure and the reliability of the unique set of Burger's model for different loading frequencies.

In the second phase, the DEM model was assembled and the internal mechanical response of asphalt mixtures has been studied. In order to reduce the calculation time, a method based on frequency–temperature superposition principle developed by Liu et al. [14] has been adopted. The ball density effect has been further investigated when using this method, which is another objective of this research. The dynamic moduli and phase angles of asphalt mixtures were predicted with 3D discrete element simulation under cyclic loading conditions. By comparing the simulation results with those measured in the laboratory, the predictions of the micromechanical model were validated. In addition, the internal stresses under dynamic loading have been studied.

3. Phase 1

3.1. Laboratory tests

The mechanical properties of the asphalt mixture, used for the calibration of the Burger model, were measured in the Vienna University of Technology. The mixture is a Stone Mastic Asphalt with a maximum aggregates dimension of 11 mm (SMA 11). The adopted bitumen was Polymer modified 45/80-65.

The measurements were collected through a Frequency Sweep test in Direct Tension Compression (DTC) configuration [15]. The test was performed in strain control condition. A sinusoidal strain was applied on a cylindrical sample glued on two steel plates