Construction and Building Materials 98 (2015) 366–375

Contents lists available at ScienceDirect

Construction and Building Materials

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

Study of normal and shear material properties for viscoelastic model of asphalt mixture by discrete element method

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HIGHLIGHTS

- Discrete element model could capture the viscoelastic behavior of asphalt mixture.
- Considering both normal and shear material properties improves modeling accuracy.
- Maxwell element in Burger's model has a more dominant effect on dynamic properties.
- Normal direction model property is more significant under compressive dynamic test.

ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form 14 August 2015
Accepted 19 August 2015
Available online 27 August 2015

Keywords:
Viscoelastic
Burger' model
DEM
Normal and shear properties
Asphalt mixture

ABSTRACT

In this paper, the viscoelastic behavior of asphalt mixture was studied by using discrete element method. The dynamic properties of asphalt mixture were captured by implementing Burger's contact model. Different ways of taking into account of the normal and shear material properties of asphalt mixtures have been reviewed. Two models, Model I and Model II, with different design parameters were developed and compared. For Model I, Burger's model parameters in normal and shear direction were calibrated by using laboratory test results from Frequency Sweep Test performed in both normal and shear direction, respectively; while for Model II, the same calibrated parameters in the normal direction were used, but the values for the shear direction were chosen to be equal with the normal direction. The complex modulus of asphalt mixtures were predicted for both optimized models by conducting DE simulation under dynamic strain control loading. A sensitivity study was carried out, where the effects of different design parameters on the dynamic properties of asphalt mixture has been investigated, including the eight parameters of Burger's model and the friction coefficient.

1. Introduction

Discrete element method (DEM) has been commonly used for asphalt mixture simulation thanks to the advantage of being able to distinguish different material components at micro scale, such as aggregate, mastic and air-void. A commercial software named *Particle Flow Code 3D* (*PFC*^{3D}) has gradually gained its popularity during the past 30 years because of the convenience for implementation. The normal procedure for DEM model generation mainly comprises two steps: first the geometrical model should be created, and then different contact models could be assigned, which describe the physical behavior occurring at a contact between distinct elements. When defining the contact, material properties both in normal and shear direction need to be taken into account. The viscoelastic normal and shear properties of asphalt mixtures could be obtained by conducting the corresponding normal and shear test configurations in the laboratory. However, due to the limited resources of approved test machine and lack of standard for testing shear properties in Europe, usually only the material properties in normal direction are available. Different models have been developed for capturing the viscoelasticity of asphalt mixture material, and the shear properties of the material have been considered in many different ways by researchers when implementing those models in DEM. Therefore, it's necessary to address the importance of assigning the accurate shear properties when implementing DEM.

For viscoelastic materials, models comprise spring and dashpots could be used in order to capture material's time dependent response under different loading conditions. The most common and widely used models are the Maxwell Model and the Kelvin

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http://dx.doi.org/10.1016/j.conbuildmat.2015.08.116
0950-0618/

Model. Whereas, both models are limited in their representation of the actual viscoelastic behavior; the former is able to describe stress relaxation, but only irreversible flow; the latter can represent creep, but without instantaneous deformation, and it cannot account for stress relaxation. A combination of both elements, the Burger's model, offers more possibilities, as shown in Fig. 1 (a). It is well suited for a qualitative description of creep [1].

For the usage of PFC^{3D}, mainly two strategies have been developed for considering the viscoelasticity of the asphalt material. The first one is to use a modified linear contact model, where the normal and shear sphere stiffness change with loading time based on the Burger's constitutive relation: when Burger's model is subjected to a constant load , three types of deformation could be distinguished: the spontaneous elastic deformation from the spring, $\varepsilon_1 = \sigma/E_1$; the delayed elastic deformation from the Kelvin element, $\varepsilon_2 = \sigma/E_2[1 - exp(-t/\tau) + t/\eta_1]$; the irreversible creep from the dashpot, $\varepsilon_3 = \sigma(t/\eta_1)$ [2]. Therefore, the total deformation, as shown in Fig. 1(b), is

$$\varepsilon_{tot} = \sigma\left[\frac{1}{E_1} + \frac{1}{E_2}\left(1 - exp(-t/\tau) + \frac{t}{\eta_1}\right)\right] \tag{1}$$

Dondi [3] modeled the DSR complex shear modulus of asphalt binder by using this method, and the same properties have been assigned to both normal and shear direction.

There is one build-in *Simple Viscoelastic Model* available in PFC^{3D}, which is simply just a *Maxwell model*. Nevertheless, due to its simplicity discussed earlier, it's not efficient enough to capture the complicated viscoelastic behavior of asphalt mixture. Most researchers used the *Burger's Contact Model* embedded in PFC directly, which makes the alternative option. In Liu's study [4], the relationship of Burger's contact model parameters for asphalt mastic was developed as following Eq. (2):

$$K_s^{BCM} = \delta K_n^{BCM} \tag{2}$$

where, K_n^{BCM} represents the parameters of Burger's contact model in the normal direction, while K_s^{BCM} in the shear direction. It was found that δ had little effects on the DE model. In Adhikari's viscoelastic model [5], the same relation has been used and δ was taken as 1. It was also chosen to equate the normal and shear direction parameters in the study of Feng [6].

Some other perspectives have been considered for choosing the proper ratio between normal and shear direction properties of Burger's contact model:

In Collop's study [7], the deformation behavior of an idealized asphalt mixture were modeled both for elastic and viscoelastic case. The Burger's model parameters were chosen arbitrarily by matching the magnitude and shape of predicted axial strain curve with the measured data of the material. The ratio between normal contact parameters and the shear contact parameters for the viscoelastic model were taken to be a factor of 10 so that the ratio of the radial strain to the axial strain would be similar to the results of the elastic case. The same method was carried on by Cai [8], except the ratio between normal and shear direction was increased to 11.

In Cai's study [9,10], a series of uniaxial compression simulation were performed over a range of ratios of contact stiffness and normal and shear contact stiffness of the particles. The results show that the Poisson's ration only depends on the ratio of contact stiffness and not the absolute values, and the shear and torsion contact parameters should be taken as a factor of 1.75 smaller than the normal and bending contact parameters so that the Poisson's ratio would be 0.32.

Liu [11] developed the conversion from macroscale properties to microscale model parameter. The ratio between normal contact parameters and the shear contact parameters for Burger's model parameters were taken to be a factor of $2(1 + \nu)$ due to the fact that the constitutive relation $E = 2G(1 + \nu)$ was used, where, E is the Young's modulus, G is the shear modulus and ν is the Poisson's ratio. The same approach has been used in Liu's following studies [12–15]. It is obvious that when the Poisson's ratio is taken as 0.5, the factor will yield the value of 3, which has been used directly by Collop [16,17].

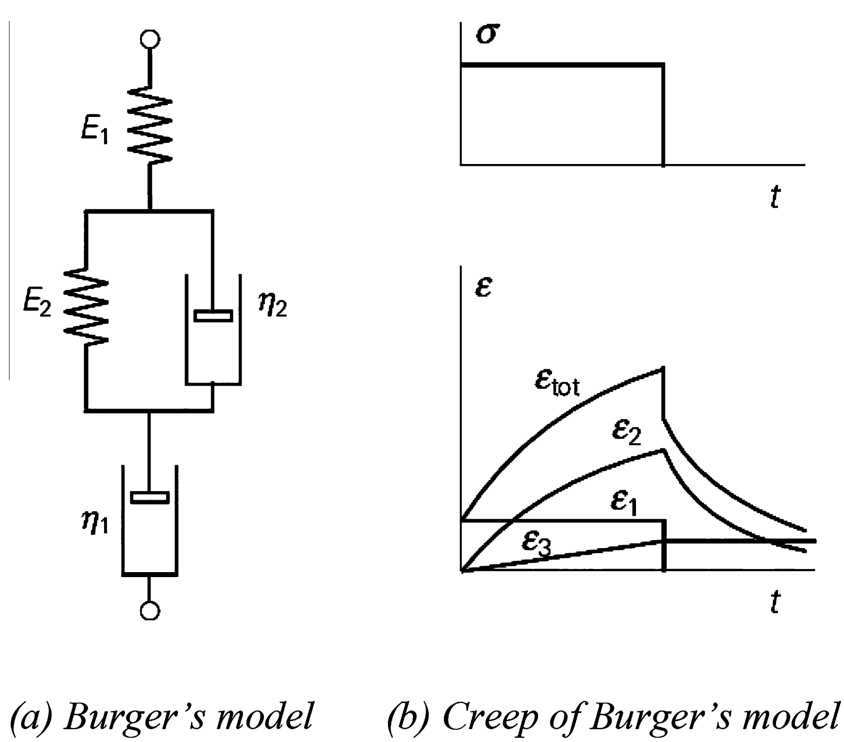

Fig. 1. Creep of Burger's model.