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Discrete element visco-elastic modelling of a realistic graded asphalt mixture

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Abstract

The Discrete Element Model has been used here to simulate constant strain rate uniaxial compression tests for a realistic asphalt mixture comprising graded aggregates. A numerical sample preparation procedure has been developed to represent the physical specimen. A parallel bond model has been used in the elastic modelling to give moment resistance at the contacts. Uniaxial constant strain rate loading and unloading tests have been simulated. 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, and the loading speed have been investigated. A modified Burger′s model has been used to introduce time-dependent contact stiffness with the ability to transmit moment and torsion. Two-ball clumps have been used to investigate the effect of particle shape. The effect of Burger′s model parameters, the ratio of normal to shear Burger′s model parameters, the bond radius multiplier, the friction coefficient and the bond strength distribution in the viscoelastic simulations have been investigated. Constant strain rate uniaxial compression tests have been undertaken in the laboratory where the axial stress–strain response has been measured for comparison with the numerical modelling results. The modified Burger′s model has proved to be useful and ready for simulating uniaxial constant strain rate and creep tests in the laboratory.
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Keywords: DEM; Asphalt; Parameters study; Elastic; Visco-elastic

1. Introduction

Asphaltic material has been one of the most popular materials used in the surface of pavements since the end of the 19th Century. Asphalt mixture is a complex material which comprises at least three components: bitumen, graded mineral aggregates and air. The macromechanics of an asphalt mixture is largely dependent on the micromechanics among the three components. There are two main types of load failure in asphaltic pavement: cracking (fatigue) and rutting (permanent deformation). Laboratory research can offer valuable information to explain the damage mechanism of asphalt mixtures; however, this information is limited to macroscopic observation. The micro-scale constitutive relationship is an important factor in terms of overall material performance. Therefore, it is useful to build a model in order to properly represent the microstructure of asphalt mixtures and to understand the constitutive relationship from the microscopic point of view.

Over the past two decades, the discrete element method (DEM) has been used by many researchers to simulate the microstructure of asphalt mixtures. Three main methods have been used: a highly idealised method (Collop et al., 2006, 2007), a randomly created polyhedron method (Liu and You, 2009) and an image-based method (Adhikari and You, 2008).

In the highly idealised method, the mechanical behaviour of idealised asphalt mixtures is modelled. Idealised asphalt mixtures comprise approximately single-sized sand mixed with

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bitumen. Aggregates are simulated as balls with single-size or two-ball clumps with the same volume. Therefore, the grading of the aggregates is not considered. Also, the contact bond used to bond the particles cannot provide moment resistance or stop the particles from rolling, spinning or becoming torsional. However, this is a necessary step to further development in the discrete element modelling of real asphalt mixtures with more realistic contact models.

In the randomly created polyhedron method, aggregates are simulated with randomly created polyhedron assemblies made with a large number of spheres. The generated polyhedron assembly provides a good representation of the actual geometry of aggregates and the sample generation method is laboratory-independent. This method also makes it possible to model the cracks around or through aggregates during strength tests. However, the method has proved to be time-consuming due to the large number of particles involved.

The image-based method is based on the microstructural image of materials using X-Ray CT. The shape and the distribution of aggregates can be represented well by this model. However, as it is laboratory-dependent, expensive laboratory equipment and well-trained technicians are required.

So far, the models used to represent the mechanical behaviour of asphalt mixtures include an elastic model (Buttlar and You, 2001), a viscoelastic model (time-dependent behaviour) (Abbas et al., 2007) and a cohesive model (Kim et al., 2008).

The aim of this paper is to produce a validated discrete element model (laboratory-independent) to simulate uniaxial compression tests on a realistic asphalt mixture comprising graded aggregates, to improve the understanding of the micromechanical behaviour of realistic asphalt mixtures and to produce guidelines related to parameter determination procedures.

2. Discrete element modelling

The discrete element method (DEM) was developed by Cundall Peter and Strack Otto (1979) to model granular materials from a microstructural perspective. The Particle Flow Code in three dimensions (PFC3D) (ITASCA, 2008b) was developed by the ITASCA Consulting Group Inc. to model the movement and the interaction of spherical particles using DEM. Compared with Liu and You (2009)′s model, the model in this paper considers the bitumen via a simple contact law, whilst still facilitating micro-cracks and bulk fractures. In our model, the aggregates are modelled as spherical particles or clumps (two or more particles combined together). The binder is not modelled explicitly, but is represented by a constitutive model (parallel bond model/Burger′s model), which reduces the computation time. The same strategy has been used by Chen et al. (2012b, 2012a) to simulate Superpave gyratory compaction and to analyse the air void distribution in asphalt mixtures with YADE. The particles displace independently from each other and interact only at contact points; the soft contact approach is used when the particle is assumed to be rigid, but allowed to overlap at contact points for a small range compared with particle size. The contact force is related to the overlap and calculated via a force–displacement law. The particle displacement is calculated from the interparticle forces using Newton′s 2nd law. More details can be found in ITASCA (2008b).

Particles are allowed to be bonded together at contact points. The bonds will break when the predefined bond strength is reached. A bond known as the parallel bond (linear contact model) describes the constitutive behaviour of a finite-sized piece of binder material between two particles. It can be imagined as a set of elastic springs uniformly distributed over a circular disk lying on the contact plane. These bonds establish an elastic interaction between particles that acts in parallel with slip, and hence, its name. It can transmit both forces and moments between particles. Typical parameters which need to be specified are Young′s modulus of the particle (E) and the parallel bond ($\overline{E}$), the ratio of normal to shear stiffness of the particle (n) and the parallel bond ($\overline{n}$), normal ($\overline{\sigma}$) and shear ($\overline{\tau}$) bond strengths, the bond radius multiplier (λ), and the friction coefficient of the particles (f) and of the walls (f_w). The normal stiffness of the particles (Knp) and of the parallel bonds (Knb) is calculated from Eqs. (1) and (2) (Potyondy and Cundall, 2004). The shear stiffness is calculated from the ratios of normal to shear stiffness (Eqs. (3) and (4)).

$$Knp = 4RE \tag{1}$$

$$Knb = \frac{\overline{E}}{R^A + R^B} \tag{2}$$

$$Ksp = Knp/n \tag{3}$$

$$Ksb = Knb/\overline{n} \tag{4}$$

where R is the particle radius, R^A and R^B are the radii of two balls which are in contact, Ksp is the shear stiffness of the particle and Ksb is the shear stiffness of the parallel bond. The units of parallel bond stiffness in Eqs. (2) and (4) are Pa/m; thus, the real parallel bond stiffness is given by

$$K = Knb \times \pi[\lambda \times \min(R^A, R^B)]^2 \tag{5}$$

where $\min(R^A, R^B)$ is the minimum radius of the two balls in contact and λ is known as the radius multiplier.

The maximum tensile stress and the shear stress acting on the parallel bond periphery are calculated based on the beam theory and given by

$$\sigma^{\max} = \frac{-F^n}{A} + \frac{|M^s|\overline{R}}{I} \tag{6}$$

$$\tau^{\max} = \frac{|F^s|}{A} + \frac{|M^n|\overline{R}}{J} \tag{7}$$

where F^n and F^s are the normal and the shear forces, respectively, M^n and M^s denote the axial and the shear directed moments, respectively, $\overline{R}$ is the radius of the imagined circular disk, and A, I and J are the area, the moment of inertia and the polar moment of inertia of the parallel bond cross section, respectively. I and J are given by

$$I = \frac{1}{4}\pi\overline{R}^4 \tag{8}$$

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