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Micromechanical response of aggregate skeleton within asphalt mixture based on virtual simulation of wheel tracking test

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HIGHLIGHTS

- Three-dimensional discrete element model was built to depict asphalt mixture.
- Virtual wheel tracking test was built to predict rutting of asphalt mixture.
- Translation and rotation of coarse aggregates during rutting were revealed.
- Contact condition and force within aggregate skeleton during rutting were analyzed.

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ABSTRACT

Based on the discrete element method (DEM), this study conducted the virtual simulation of wheel tracking tests to predict the rutting deformation of asphalt mixtures and analyzed the micromechanical response of aggregate skeletons within the asphalt mixture during the tests. Considering the irregular shape and elastic property of coarse aggregates, the continuum and viscoelastic property of the asphalt mastic and the random distribution of air voids in the asphalt mixture, a three-dimensional micromechanical DEM model for asphalt mixture was constructed by particle flow code in three dimensions (PFC3D). A two-dimensional virtual asphalt mixture sample was generated based on the central cross-section of the three-dimensional virtual asphalt mixture sample. A virtual wheel tracking test was built by PFC3D and verified by laboratory wheel tracking tests to predict the rutting behavior of the asphalt mixture. During the virtual wheel tracking test, the movements of the coarse aggregates, including their translation and rotation, were revealed, and the contact condition and contact forces within the aggregate skeleton were analyzed. The micromechanical responses of the aggregate skeleton demonstrate how the aggregate skeleton in asphalt mixtures bears the load and describes the potential reasons why rutting deformation forms from the micromechanical view.

1. Introduction

Asphalt mixtures have been commonly used in pavement construction. Due to the creep property of asphalt mixtures, rutting is shown as permanent deformation in the wheel paths and is one of the most serious distresses of asphalt pavement [1]. The design of asphalt mixtures with satisfactory rutting resistance is important to prevent the rutting distress of asphalt pavement during its service life [2]. To evaluate the creep behavior and rutting resistance of an asphalt mixture, many laboratory tests have been developed and applied when designing such mixtures as static creep tests, dynamic creep tests, wheel tracking tests, Hamburg rutting tests, and asphalt pavement analyzers [3–8]. However, due to the heterogeneity of asphalt mixtures and complex artificial interferences, it is difficult to control the variability of laboratory tests. Meanwhile, most laboratory tests can only obtain the macro-property of asphalt mixtures but cannot depict the micromechanical response of an asphalt mixture, which is more helpful to understand its rutting behavior.

Currently, the finite element method (FEM) and the discrete element method (DEM) are two major numerical methods utilized to characterize the mechanical performance of asphalt mixtures. During FEM analysis, an asphalt mixture is typically treated as a homogeneous material [9,10]. However, an asphalt mixture is a heterogeneous material composed of various ingredients, including

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aggregates, asphalt binder and air voids. To capture the heterogeneity and microstructure of an asphalt mixture, FEM models were studied to build the random aggregate structures of an asphalt mixture [11–13]. It is demonstrated that a FEM model with random aggregate structures can characterize the irregular shape and angularity of coarse aggregates within asphalt mixtures. However, FEM models with random aggregates structures for asphalt mixtures are still based on continuum theory; the theory still has difficulties in modeling the contact changing of various ingredients coming in and out of contact and the sliding behavior between different ingredients within an asphalt mixture [14,15]. DEM can analyze the interaction among discrete particles in contact by modeling the translational and rational behavior of each particle based on Newton's second law of motion and a finite difference scheme [16,17]. Therefore, compared to FEM, DEM provides a more promising way to model and characterize the microstructural features of an asphalt mixture by treating it as a multiphase material.

Cundall developed DEM for the analysis of rock mechanics, and the method was later applied to granular materials [18,19]. After bonded contact models were developed, DEM was successfully applied to solid materials and introduced to the analysis of asphalt mixtures [20,21]. Amongst the various discrete element codes, particle flow code in two and three dimensions (PFC2D/3D) was popularly used for asphalt mixtures due to its higher computation efficiency and ability to model the fracture behavior, interaction and interface conditions between the various ingredients of the mixture [17,22]. In recent decades, various studies have utilized DEM to analyze the micromechanical behavior of asphalt mixtures. By simulating the aggregate and mastic with a mesh of small disk-shaped particles in DEM modeling, Khattak et al. predicted the dynamic modulus of asphalt mixtures under indirect tension mode [23]. To simulate the viscoelastic behavior of asphalt mixtures, Abbas et al. presented a methodology to analyze the viscoelastic response using DEM [24]. Liu et al. built a DEM viscoelastic model to study their creep stiffness [25]. Combined with image-based techniques, You et al. reconstructed the three-dimensional structure of asphalt mixtures using a combination of different layers of two-dimensional images of asphalt mixtures to predict their modulus [26]. Kim et al. studied the discrete fracture modeling for asphalt mixtures and investigated their fracture behavior [27]. Khattak et al. developed a two-dimensional DEM model of asphalt mixtures to simulate the strength and modulus [28]. To overcome the reliance of DEM modeling on image-based techniques, Liu et al. and Zhang et al. investigated the algorithms to randomly generate three-dimensional DEM models for asphalt mixtures [29,30]. With three-dimensional DEM, Chen et al. predicted mixture-cracking behavior [31]; Dongdi et al. modeled the shear modulus of asphalt binders [32]. Hou et al. investigated the mechanical response of asphalt mixtures under vehicle loading [33].

Although good progress has been achieved in previous studies, the understanding of the micromechanical behavior of asphalt mixtures is not been completely understood. The majority of the aforementioned studies concentrated on asphalt mixture modeling, as well as evaluating the stiffness/modulus of the mixture and its fracture behavior. It is necessary to develop micromechanical models to predict the rutting behavior of asphalt mixtures and to understand their micromechanical responses during rutting deformation. Rutting resistance is one of the most important required performances of asphalt mixtures, and it is demonstrated that the aggregate skeleton of such mixtures provides important contributions to their rutting resistance [34–36]. Thus, this study focused on the virtual simulation of wheel tracking tests to predict the rutting behavior of asphalt mixtures and to investigate of the micromechanical response of the aggregate skeleton during rutting deformation.

2. Materials and laboratory test

2.1. Materials

SBS modified asphalt with a performance grade of 76–28 was used to prepare a control asphalt mixture with a nominal maximum aggregate size of 13.2 mm. A dense-graded asphalt mixture (named as AC13) with a designed air void content of 4% was prepared based on the Marshall mix design [37]. The mixture's asphalt content was 4.8%, and the designed gradation is shown in Table 1.

According to the designed asphalt mixture, asphalt mastic composed of asphalt binder and fine aggregates smaller than 2.36 mm (including mineral filler) was prepared for a uniaxial static creep test to determine the parameters of the macroscale Burger's model for the mastic. The asphalt content of the asphalt mastic was 11%, and its gradation is shown in Table 2. Because the asphalt mastic has good flowability due to its high asphalt content, its air void content was assumed to be zero.

2.2. Laboratory test

As shown in Fig. 1, the laboratory tests used in this study follow the standard Chinese specification procedures [38]. A Universal Testing Machine (UTM) was used to conduct a uniaxial static creep test at 60 °C to measure the creep compliance of the asphalt mastic. A cylindrical specimen with height of 150 mm and diameter of 100 mm was used for the test. The applied static axial stress was kept constant at 0.07 MPa. A wheel tracking test was conducted at 60 °C to measure the rutting deformation and to calculate the dynamic stability of the designed asphalt mixture. A slab specimen with a length and width of 300 mm and height of 50 mm was used during the wheel tracking test. A rubber wheel rolled back and forth on the specimen for 1 h at a speed of 161 mm/s, and the moving distance on the specimen was 230 mm. The total weight of the rubber wheel was 78 kg, and the pressure applied by the wheel rubber on the specimen was 0.7 MPa. During the wheel tracking test, the dynamic stability is used to describe the rutting resistance of asphalt mixture and is calculated by Eq. (1):

$$DS = \frac{15N}{d_{60} - d_{45}} = \frac{42 \times 15}{d_{60} - d_{45}} \tag{1}$$

where DS is the dynamic stability, N is the wheel loading times per minute (42 times/min), and d_{45} and d_{60} are the vertical displacement (rutting depths) under wheel loading at 45 and 60 min, respectively.

3. Modeling of the virtual wheel tracking test

3.1. Micromechanical modeling of the asphalt mixture

To simplify the micromechanical modeling of the asphalt mixture by PFC3D, the mixture was divided into three constituents including coarse aggregates larger than 2.36 mm, asphalt mastic composed of asphalt binder and fine aggregates smaller than 2.36 mm, and air voids. It is considered that coarse aggregates form the aggregate skeleton in the mixture, the asphalt mastic fills into the voids of the aggregate skeleton, and the air voids randomly distribute within the asphalt mastic.

Table 2
Gradation of asphalt mastic.

Sieving size/mm	2.36	1.18	0.6	0.3	0.15	0.075
Passing ratio/%	100	56	41.5	25.4	18.3	13.6

Table 1
Designed gradation of AC13.

Sieving size/mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing ratio/%	100	96.8	80.5	60.6	40.5	22.7	16.8	10.3	7.4	5.5