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Heterogeneity effect of mechanical property on creep behavior of asphalt mixture based on micromechanical modeling and virtual creep test

Tao Ma[a,*], Hao Wang[b], Deyu Zhang[c], Yao Zhang[a]

[a] School of Transportation, Southeast University, 2 Sipailou, Nanjing, Jiangsu 210096, China
[b] Department of Civil and Environmental Engineering, Rutgers, State University of New Jersey, 96 Frelinguysen Rd, Piscataway, NJ 08854, USA
[c] Department of Civil Engineering and Architecture, Nanjing Institute of Technology, 1 Hongjing Road, Nanjing, Jiangsu 211167, China

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ABSTRACT

Based on laboratory tests and discrete element method (DEM), this study investigated the influences by mechanical property heterogeneity of different ingredients of asphalt mixture on the creep behavior of asphalt mixture. By considering the important material features and mechanical properties of different ingredients, such as the three-dimensional irregular shapes and elastic properties of coarse aggregates, the continuous characteristics and viscoelastic properties of asphalt mastic, and the random distribution and zero mechanical property of air voids within asphalt mastic, micromechanical modeling of asphalt mixture and virtual uniaxial static creep test was built by using PFC3D. Weibull distribution was used to describe the heterogeneity of mechanical property for coarse aggregates and asphalt mastic within asphalt mixture. And the influences of the mechanical property heterogeneity of aggregates and asphalt mastic on the creep behavior of asphalt mixture were evaluated based on virtual creep test. The results show that the built discrete element model and virtual test can well predict the creep behavior of asphalt mixture. Both the heterogeneity of mechanical property of aggregates and mastic have negative influences on the creep behavior of asphalt mixture by affecting the distribution of micromechanical forces within asphalt mixture. And heterogeneity of mechanical property of coarse aggregates causes more obvious influences. It is important to guarantee the homogeneity of mechanical property of coarse aggregates and asphalt mastic within asphalt mixture to resist creep deformation.

1. Introduction

Creep of asphalt mixture at high temperature leads to rutting and damage of asphalt pavement which is one of the most serious premature distresses of asphalt pavement (Zhang et al., 2012, Xu and Huang, 2012). Understanding the micromechanical mechanism of creep property of asphalt mixture at high temperature is important for design asphalt mixture and pavement with satisfied high-temperature mechanical performance (Zhang et al., 2013, Zhang et al., 2015). Previous studies referring to the creep property of asphalt mixture were mainly based on laboratory and field experimental tests (Xu et al., 2014; Huang and Zhang, 2010; Suh and Cho, 2014; Liao et al., 2013; Zhang et al., 2012). However, it is difficult to control the variability of experimental tests due to the complex artificial and environmental interferences. Meanwhile, most of the experimental approaches are time-consuming and involve considerable labor efforts and financial cost.

As an emerging numerical method, the discrete element method (DEM) can analyze particulate system by modeling the translational and rational behavior of each particle using Newton's second law with appropriate inter-particle contacts. It was first developed for analysis of rock mechanics, and then applied to soil mechanics (Cundall and Strack, 1979). After bonded contact models were developed, it can also be applied to solid materials and was introduced to analyze the micromechanical behavior of asphalt mixture (Chang and Meegoda, 1997; Zhong and Chang, 1999). After the initial Ball codes by Cundall and Strack, different kinds of DEM computing codes have been developed and used, such as Trubal which is a revised version of Ball, universal distinct element code (UDEC), discrete element code in three dimensions (3DEC), and particle flow code in two and three dimensions (PFC2D/3D) (Hart et al., 1988; Chen and Hung, 1991; Dickens and Walker, 1996; Buttlar and You, 2001; Washington and Meegoda, 2003; Abbas et al., 2007; Idris et al., 2008). Based on DEM method, many re-

* Corresponding author.
E-mail address: matao@seu.edu.cn (T. Ma).

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Table 1
Gradations of asphalt mixture, coarse aggregates and asphalt mastic.

Sieving size /mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
				Asphalt mixture						
Passing ratio / %	100	96.8	80.5	60.6	40.5	22.7	16.8	10.3	7.4	5.5
				Coarse aggregates						
Passing ratio / %	100	94.6	67.2	33.8	0.0	/	/	/	/	/
				Asphalt mastic						
Passing ratio / %	/	/	/	/	100	56	41.5	25.4	18.3	13.6

searches have been conducted to characterize the mechanical behavior of asphalt mixture in the past decades. You et al. developed two-dimensional image-based micromechanical models to predict asphalt mixture stiffness and reconstructed the three-dimensional structure of asphalt mixture by using a combination of different layers of two-dimensional images (You and Buttlar, 2004; You et al., 2008). Chen et al. predicted the cracking behavior of asphalt mixture based on discrete element method (Chen et al., 2012). To analyze the viscoelastic behavior of asphalt mixture, Liu et al. investigated the equivalent viscoelastic model for discrete element simulation of asphalt mixture and conduct simulation of asphalt mixture based on discrete element models (Liu et al., 2009; Liu and You, 2009). Dongdi et al. analyzed the performance of granular mixes and modeled the DSR complex shear modulus of asphalt binder based on discrete element approach (Dondi et al., 2012, 2014). Khattak et al. built image-based discrete element model for hot mix asphalt mixtures (Khattak et al., 2015). Chen et al. used discrete element method to simulate the compaction and air-void distribution of asphalt mixture (Chen et al., 2013). Zhang et al. and Hou et al. developed algorithms to conduct discrete element modeling for asphalt mixture and investigated the micro-mechanical response of asphalt mixture (Ministry of Transport of the People's Republic of China, 2006, 2011). However, few researches were conducted to characterize the high-temperature creep property of asphalt mixture based on three-dimensional discrete element modeling and the influences by the mechanical property heterogeneity of asphalt mixture on its creep deformation.

The main objectives of this study are to characterize the high-temperature creep behavior of asphalt mixture using DEM-based virtual testing and analyze the effect of mechanical property heterogeneity of different ingredients within asphalt mixture on the creep deformation of asphalt mixture. Since particle flow code (PFC) is a commonly used DEM code in simulation of asphalt mixture due to its high computation efficiency and flexible user-defining procedure, micromechanical modeling of asphalt mixture and virtual simulation of uniaxial static creep test were conducted by using PFC3D. The mechanical property heterogeneity of coarse aggregates and asphalt mastic were described by Weibull distribution and their influences on the creep behavior of asphalt mixture were evaluated.

2. Materials and testing procedures

2.1. Materials

A dense-graded asphalt mixture named as AC-13 was prepared based on Marshall mix design (Ministry of Transport of the People's Republic of China 2006) in this study. The aggregate gradation is shown in Table 1. This reference asphalt mixture was used in the laboratory tests and virtual modeling. Based on this reference asphalt mixture, asphalt mastic composed of asphalt binder and fine aggregates smaller than 2.36 mm was also prepared for conduction of uniaxial static creep test to get the micromechanical parameters in the virtual modeling in Section 3. The gradations for coarse aggregates and asphalt mastic are also shown in Table 1. The asphalt content of asphalt mixture is 4.8% with design air void content of 4%. The asphalt content of asphalt mastic is 11.0%. Due to the fine gradation and high asphalt content of asphalt mastic, its air void content is considered as 0%.

2.2. Laboratory tests

The uniaxial static creep test was conducted using by Universal Testing Machine (UTM) for the designed asphalt mixture and asphalt mastic. The test temperature was 60 °C and the applied axial stress was kept constant. The applied axial stresses were 0.7 and 0.07 MPa for asphalt mixture and asphalt mastic, respectively. The samples of asphalt mixture were prepared by gyratory compaction (Ministry of Transport of the People's Republic of China, 2011). Due to the high flowability of asphalt mastic because of its fine gradation and high asphalt content, the samples of asphalt mastic were prepared by vibration instead of compaction using the same mold with asphalt mixture. Fig. 1 shows the test samples which are cylindrical specimens with height of 150 mm and diameter of 100 mm for asphalt mixture and asphalt mastic for laboratory creep tests.

3. Micromechanical modeling and virtual test

3.1. Micromechanical models and parameters

Based on previous studies (Hou et al., 2015; Zhang et al., 2012; Chen et al., 2015) and trial simulation tests, considering the computation efficiency of PFC3D in microstructure modeling and virtual simulation, to simplify the PFC3D modeling, asphalt mixture is modeled as a combination of three ingredients including coarse aggregates (aggregates larger than 2.36 mm), asphalt mastic (composed of asphalt binder and fine aggregates smaller than 2.36 mm), and air voids. Coarse aggregates with irregular shapes mainly form the three-dimensional skeleton of asphalt mixture and the asphalt mastic was considered as continuum medium filling into the voids of coarse aggregate skeleton. Although the distribution of air voids in asphalt mixture is very complex and usually related to the compaction process, previous studies (Hou et al., 2015; Zhang et al., 2012; Chen et al., 2015) proved that it is reasonable to assume random distribution of air voids in the asphalt mixture to conduct performance analysis. Since this study mainly focusing on the effect by property heterogeneity of aggregates and asphalt mastic on the performance of asphalt mixture, to simplify the modeling procedure and analysis, air voids were considered to randomly distribute in the asphalt mastic.

During PFC3D modeling, different contact models were used to describe the micromechanical behavior of different ingredients (Itasca Consulting Group, 2008). Since the microstructure of asphalt mixture was modeled as a three-phase system (coarse aggregates, asphalt mastic, and air voids), three types of contacts exist within the micromechanical modeling of asphalt mixture, which are contacts between aggregates, within asphalt mastic, and between aggregate and asphalt mastic. Since the viscoelastic properties of asphalt mastic have important effects on the creep behav-