Construction and Building Materials 166 (2018) 334–344

Contents lists available at ScienceDirect

Construction and Building Materials

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

Impacts of air-void structures on the rutting tests of asphalt concrete based on discretized emulation

Yao Zhang, Tao Ma *, Xuanhao Ding, Tian Chen, Xiaoming Huang, Guangji Xu

School of Transportation, Southeast University, 2 Sipailou, Nanjing, Jiangsu 210096, China

HIGHLIGHTS

- Algorithms for performing virtual wheel tracking test were built.
- Air-void structures with different porosity, distribution and sizes were generated.
- The effects of air-void structures on virtual rutting tests were discussed.

ARTICLE INFO

Article history:
Received 11 September 2017
Received in revised form 23 January 2018
Accepted 24 January 2018
Available online 22 February 2018

Keywords:
Discretized emulation
PFC 3D
Rutting resistance
Air-void structure
Dense-graded asphalt concrete

ABSTRACT

To investigate the impacts of inner air-void structures on the high temperature performance of dense-graded asphalt concrete, the digital models of rutting plate composed of asphalt mastics, coarse aggregates and porosity were constructed by the discretized emulating software PFC 3D. Then, curves of rutting depth during virtual rutting tests were recorded, which matched with the laboratory-measured results. The similarity between these test curves verified that the virtual rutting test can be a feasible way to predict the rutting behavior of asphalt concrete. After that, the inner structure characteristics of air voids including porosity, size, horizontal and vertical distribution were put into the emulation software to investigate their effects on rutting behavior. Results show that larger porosity in asphalt concrete leads to worse rutting resistance, and this is especially true when air voids are concentrated in the middle section of the testing sample. In fact, the middle section contributes most to the rutting formation compared with other sections. In terms of vertical distribution, air voids concentrated in the mid-upper region of rutting plate have adverse effects on the rutting resistance. Moreover, sizes of air voids also influence the rutting behavior and the impact depends on aggregate gradations.

1. Introduction

Being caused by the growth of long-term deformation of all individual asphalt layers, rutting has become one of the leading distresses in asphalt pavement [1]. The dynamic stability and rutting depth are greatly affected by the inner characteristics of asphalt concrete such as air-void structures [2,3]. The air-void feature within pavement varies constantly under the action of long-term repeated load and growing traffic, while the variation process of porosity during densification process cannot be well monitored and recorded in laboratory test [2]. Because of the inadequacy of indoor tests, researchers in earlier studies mostly dedicated to the impacts of initial porosity within concrete specimen on permanent deformation. However, even in parallel specimens under the same loading conditions, results of dynamic stability and rutting curves may be different [4,5]. Researches indicate that the rutting behavior of mixture is not only associated with its composition and initial porosity, but also related to meso-scale spatial distribution of its components and air voids. This should be studied by using more effective test methods.

In recent years, image analysis systems such as ground penetrating radar (GPR) measurements and X-ray computed tomography (CT) techniques were widely utilized to characterize the structure of air voids within asphalt mixture. Babatunde et al. applied X-ray CT scanning to distinguish three-dimensional traits like volume, size, abundance and sphericity of air voids in high performance concrete [6]. Zhang et al. combined X-ray CT scanning, mercury intrusion porosimetry, gas physical adsorption method and linear traverse method to quantify the size and other characteristics of pore structures which were greater than 0.35 mm within concrete [7]. Hassan et al. employed an image analysis

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

https://doi.org/10.1016/j.conbuildmat.2018.01.141
0950-0618/

equipment to help describe the inner structural damage of concrete based on X-ray images [8]. Du et al. obtained a reconstructed structure of concrete composed of aggregate particles, mortar matrix and porosity by X-ray CT image analysis [9]. A high speed Non-Destructive Testing (NDT) technique with GPR was applied by Chen et al. to measure the field porosity, which was used to generate the porosity contour maps [10]. Khan and Collop used X-ray CT to characterize the three phases of asphalt mixture and to monitor the micro-damage growth in fatigue test under tension-compression cyclic test condition [11,12]. Results from these studies show that the image-based methods can appropriately depict the inner structure of air voids and damage in asphalt concrete. Besides, the image reconstruction analysis shows that the air voids within asphalt concrete have uneven distribution and irregular size, which is greatly associated with the gradation of aggregates, capacity of asphalt binder and compaction method of concrete. Although the real feature of air voids in asphalt concrete and the growth of micro-damage in loading process can be recognized by X-ray CT and GPR techniques, it may take much effort and money to evaluate changes of mechanical performance with respect to different air void structures. Therefore, to find a suitable reconstructing and reloading model to analyze the impact of air voids on rutting resistance of asphalt concrete is significantly important.

Recent studies have found that discrete element method (DEM) could be a promising way to reconstruct asphalt concrete with porosity and to simulate its rutting process under repeated external load in micromechanical view [13]. The DEM was used by Abbas et al. to analyze the viscoelastic response of concrete specimens [14]. Ma et al. also performed a high-temperature creep test and a virtual rutting test based on DEM to forecast the permanent deformation of concrete specimens [13,15,16]. In this manner, a numerical simulation method for asphalt concrete with heterogeneous material composition can be employed to investigate its high-temperature performance, which is definitely more complicated compared with the one for continuum model. Although significant progresses have been made in earlier researches, the impacts of internal air-void feature on rutting performance of rutting plates were seldom studied. Previous studies on rutting tests mainly concentrated on micro-mechanical modeling, validation of the simulation and observation of the micromechanical responses, yet few of them was dedicated to justifying the viability of the discretized method to investigate the impact of air-void structures on high temperature performance of asphalt concrete. In fact, it is of great necessity to rebuild the air-void structures in asphalt concrete in accordance with reality so as to better investigate their contributions to the long-term deformation. Hence, this paper focuses on the reconstruction of air-void features within asphalt concrete. Thereafter, emulations of virtual wheel tracking tests are performed on virtual specimens with different air-void structures to predict the rutting property.

2. Materials and indoor tests

2.1. Materials preparation

Neat asphalt with a density of 1.03 g/cm^3 and performance grade of 64-22 was utilized to prepare two kinds of asphalt concrete, and their nominal maximum sizes of aggregates were 19 mm and 13 mm, respectively. These two types of dense-graded asphalt concrete were named as AC20 and AC13, respectively. In the indoor tests, asphalt specimens with a target porosity of 4% were prepared using Marshall concrete design method. Table 1 shows the aggregate gradation and asphalt binder contents of AC13 and AC20, respectively.

Taking the stability of mechanical properties of materials and computation efficiency of the DEM software into account, the asphalt concrete in DEM was regarded to be composed of meso-scale phases including coarse aggregates, asphalt mastics and air voids. More specifically, asphalt mastics were regarded as homogenous particles composed of asphalt binder, mineral filler and fine aggregate with the nominal size smaller than 2.36 mm. The asphalt content and aggregate gradation of asphalt mastic calculated from sub sieves of fine aggregates are shown in Table 2. Specimens were prepared accordingly for following static creep tests to gain the macro-scale parameters.

The bitumen content of asphalt mastic was determined through the direct proportional relationship of specific surface area between asphalt binder and fine aggregates, which was 14% in AC13 and 12.8% in AC20, respectively. The density of asphalt mastic can be calculated as follows:

$$\rho_s = \frac{a + (a+1)\frac{V_x}{V_c}}{1 + \frac{V_x}{V_c}} \rho_c \quad (1)$$

where a is the bitumen content of asphalt mixes V_x is the volume fraction of fine aggregates; V_c is the volume fraction of coarse aggregates; ρ_c is the average density of coarse aggregates; ρ_s is the density of asphalt mastic.

2.2. Indoor tests

The creep tests and rutting tests conducted in this study strictly follow the operation procedures in Chinese specifications [17]. To be more specific, four cylinder specimens of two asphalt mastic types with 100 mm diameter and 100 mm height, as shown in Fig. 1(a), were prepared for the uniaxial creep tests. The vibration molding was used to prepare asphalt mastic specimens. This is because these specimens have relatively high asphalt binder content and thus they have high fluidity at high temperature. It is worth noting that the specimen of asphalt mastic is easy to slump under the gravity during the demoulding process at high temperatures, which may cause lateral deformation. Hence, the demoulding temperature should be strictly controlled under 10 °C. In this condition, porosity in asphalt mastic specimens can be ignored. The loading condition of creep test is shown in Fig. 1(b) and the pressure applied on the specimens was 0.07 MPa. Besides, four slab specimens of two asphalt mixture types with a side length of 300 mm and a height of 50 mm, as shown in Fig. 2(a), were prepared for rutting tests. The load exerted by tire consists of two parts: tire self-weight of 78 kg and applied pressure of 0.7 MPa. The experimental temperature applied on creep tests and rutting tests were both 60 °C. More details about volumetric composition of asphalt concrete, preparation procedures of specimens and the loading conditions of the tests were described by Ma et al. in 2016 [13].

The axial stress was monitored and the axial strain was recorded during the creep tests. Besides, the changes of rutting depth were also recorded during indoor rutting test, and the dynamic stability can be defined as:

$$DS = \frac{(t_2 - t_1) \times \upsilon t_{60}}{(d_2 - d_1) \times l} \quad (2)$$

where υ and l are the loading speed and single-trip moving distance of laboratory wheel tracking test, respectively; t_{60} is the loading time of 60 s; d_1 and d_2 are the rutting depths recorded at 45 (t_1) and 60 (t_2) minutes during the test, respectively; DS is the dynamic stability.