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Water flow simulation and analysis in HMA microstructure

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Abstract: This paper introduces a new method for reconstructing virtual two-dimensional (2-D) microstructure of hot mix asphalt (HMA). Based on the method, the gradation of coarse aggregates and the film thickness of the asphalt binder can be defined by the user. The HMA microstructure then serves as the input to the computational fluid dynamic (CFD) software (ANSYS-FLUENT) to investigate the water flow pattern through it. It is found that the realistic flow fields can be simulated in the 2-D microstructure and the flow patterns in some typical air void structures can be identified. These flow patterns can be used to explain the mechanism that could result in moisture damage in HMA pavement. The one-dimensional numerical permeability values are also derived from the flow fields of the 2-D HMA microstructure and compared with the measured values obtained by the Karol-Warner permeameter. Because the interconnected air voids channels in actual HMA samples cannot be fully represented in a 2-D model, some poor agreements need to be improved.

Key words: hot mix asphalt; microstructure; simulation; water flow

1 Introduction

HMA is a porous medium consisting of graded coarse and fine aggregates bound with asphalt binder plus a certain amount of air voids. In HMA pavement construction, it is important that the mix be adequately compacted in-place. If the air void content exceeds about 8 percent by volume, there may be interconnected channels which allow water to easily penetrate into the HMA pavement (Cooley et al. 2000; Brown et al. 2004). High permeability could result in an increased potential for moisture damage in the pavement, such as raveling and stripping. However, such a phenomenon of moisture damage and water flow pattern in HMA pavement cannot be observed on a scale visible to the human eye. Computer simulation offers attractive opportunities for depicting the simulated internal HMA structure and studying the relationship between the pore mechanism and water flow characteristics in HMA.

There are a number of attempts in the literature dealing with the water flow simulation through HMA

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pavement structure and subgrade soil. Water flow and solid mechanical simulation in an actual HMA structure captured by 2-D and 3-D X-ray computer tomography images were successfully simulated by Al-Omari and Masad (2004), Dai (2011) and You et al. (2012). Wang et al. (2003) simulated the 2-D water flow in a dual-layer soil microstructure. However the parallel flow channel between clay particles used in their model is impossible to apply here for the HMA microstructure model because of the irregularity characteristics of the HMA internal structure. The effects of permeability and tortuosity of flow through sandy soil by the Lattice Boltzmann method were analyzed by Kutay et al. (2007) and Ghassemi and Pak (2011).

In this study, we first present a new method for reconstructing a virtual 2-D microstructure of HMA. Next, we model pressure driven flow through the HMA microstructure by ANSYS-FLUENT. Finally, the simulated flow field pattern is used to explain the moisture damage mechanism. The numerical permeability values are also calculated and compared with in-lab measured values at similar air void contents.

2 HMA microstructure reconstruction

There are basically two ways of numerically reconstructing porous structures: statistics driven reconstruction and process driven reconstruction (Ganapathysubramanian and Zabaras 2007). The process driven technique was selected in this study, since the statistics driven method needs an X-ray CT image database containing information such as the inter-air voids distance distributions and the number of air voids in a fixed area or volume, which are not available in the current phase of research. In recent decades, one of the process driven methods firstly developed by Wittmann et al. (1985) has been widely used for the visual simulation of concrete, HMA and other granular materials for its simplicity. More advanced models based on this method were studied in recent years (Schutter and Taerwe 1993; Gopalakrishnan et al. 2008; Zhang 2008). In their models, the coarse aggregates are assumed as either spherical or polygon shapes and then these aggregates are randomly packed in a fixed area or volume by Monte-Carlo method. However, the problems with this model are obvious. Firstly, the roles of fine aggregates and asphalt binder in HMA cannot be represented. Secondly, this model can only produce material structures with medium to high porosity, which is not very suitable for the simulation of HMA microstructure. To solve these problems, a new method for reconstructing 2-D HMA microstructure is proposed below.

Firstly, it is assumed that all coarse aggregates in the HMA have spherical geometries as the inner spheres shown in Fig. 1(a). The asphalt binder modeled by the outer circle is used to wrap the coarse aggregate particle/inner sphere and to glue with each other to form a larger and denser solid body. The thickness of the asphalt binder is assumed to be a function of the coarse aggregate dimension and is defined to be 15% diameter of the inner sphere. Further, if we consider the area wrapped by the asphalt binder as an inscribed sphere, then the convex polygon with a random-vertices number can be generated outside as shown in Fig. 1(b). The corner areas between the exterior polygon and interior sphere are relatively small and form different triangle-like shapes. Due to the irregular shape of the corner areas, they are considered as fine aggregates. The fine aggregate acting as a stone framework bonded outside the asphalt binder can closely reflect the HMA microstructure. Finally, the overlapped plot parts are merged together to create a whole patch as shown in Fig. 1(c) to form the simplest unit of a HMA microstructure. This reconstruction method combines the approaches proposed by Lu and Torquato (1992), Bagi (2005), and Li et al. (2009). Lu and Torquato (1992) treated all aggregate particles as spheres being dispersed in asphalt binder/liquid matrix and allowed them to achieve the desired positions according to equilibrium statistics. Li et al. (2009) took aggregate shape factors into consideration which can be used to establish a relationship between fine aggregates and asphalt film thickness here. The method proposed by Bagi (2005) created a higher density packing than most constructive methods existing in this literature. In order to simulate a HMA microstructure in a larger area, many units like the type shown in Fig. 1 should be compacted or packed together. The packing algorithm follows the rule that the asphalt binder-asphalt binder, as-