Development of a three-dimensional diffusion model for water vapor diffusing into asphalt mixtures

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HIGHLIGHTS

- Developed a closed-form 3-D model for water vapor diffusing into asphalt mixtures.
- Performed Phase I water vapor diffusion tests using Gravimetric Sorption Device.
- Determined the minimum number of terms in 3-D model with satisfactory R^2 values.
- Determined diffusivities of Phase I water vapor diffusion in asphalt mixtures.
- Determined moisture retention capability of asphalt mixtures per unit mass.

ARTICLE INFO

ABSTRACT

Water vapor diffusion in asphalt mixtures has been investigated to develop water vapor diffusion models that predict the diffusivities of water vapor in asphalt mixtures. However, even the most comprehensive diffusion model available in the literature was not rigorously derived in the three-dimensional (3-D) coordinates but formulated by simply summing up the diffusion models for different directions. This study developed a closed-form 3-D diffusion model for Phase I water vapor diffusion in asphalt mixtures. The developed model was formulated through rigorous derivations originated from Fick's second law in cylindrical coordinates. The final formulation was a discrete model with infinite terms.

The developed model was applied to the data of Phase I water vapor diffusion tests performed on two types of asphalt mixtures at 20 °C using the Gravimetric Sorption Device. The initial relative humidity (RH) inside the test specimen was approximately 0% since the measuring cell where the specimen was placed was pre-vacuumed. The RH outside of the specimen was maintained at 51.51% throughout the test. The weight of the specimen was continuously measured to determine the mass of water molecules diffused into the specimen at different diffusion time points. The test data of every replicate specimen were fitted using the first 36 terms retained in the developed 3-D diffusion model in order to reduce computational efforts. A satisfied level of goodness of model fit was achieved with an R^2 value larger than 0.97. The model parameters were determined during model fitting, including the diffusivities of the Phase I water vapor diffusion in asphalt mixtures and the moisture retention capability of each specimen per unit mass. These determined parameters of the hot mix asphalt specimens (HMA) were significantly larger than those of the fine aggregate mixture specimens, which should be attributed to the larger air void contents of the HMA specimens.

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1. Introduction

Water vapor transporting in asphalt pavements is a major contributor to the moisture damage of the asphalt layers [1–6]. Researchers have demonstrated that the diffusivity of water vapor in asphalt mixtures is much larger than that of liquid water in the mixtures [1,2,5–12]. This fact indicates that water vapor may easily diffuse into an asphalt layer even though the asphalt layer is impermeable to liquid water [3,4]. For a newly constructed asphalt pavement, the asphalt layer has a relative humidity (RH) of approximately 0. Since the RH of the subgrade is always above 98% and the RH in air is usually far beyond 0 [13–19], an RH differential exists between the subgrade and the newly constructed asphalt layer, and there is also an RH differential between air and

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the asphalt layer. These two RH differentials drive water vapor to diffuse into the asphalt layer until reaching equilibrium; this procedure is considered Phase I diffusion. Upon equilibrium, the RH differential between the air and subgrade steers water vapor through the asphalt layer; this process is regarded as Phase II diffusion.

A previous study investigated the Phase I diffusion by conducting water vapor diffusion tests on cylindrical asphalt mixture specimens [20]. Diffusion models were developed for water vapor diffusion in the radial direction and in the axial direction, respectively. The model fitting demonstrated that water vapor diffused into the cylindrical specimens not only from the radial direction but also from the axial direction. Adding the diffusion models for the radial direction and for the axial direction together produced a two-dimensional (2-D) model with four unknown model parameters to be determined in the model fitting. This model was defined as a 2-D model since it provided a more comprehensive characterization of the water vapor diffusion in both radial and axial directions. However, this 2-D model in fact characterized three-dimensional (3-D) water vapor diffusion. Although the 2-D model was demonstrated to have excellent goodness of fit, it was not a rigorous diffusion model because it was not derived in the 3-D coordinates but formulated by simply summing up the diffusion models for different directions. This was an unfortunate defect of the 2-D model.

Therefore, the objective of this study was to develop a rigorous closed-form 3-D diffusion model with solid theoretical support for water vapor diffusing into cylindrical asphalt mixture specimens. The development of the 3-D diffusion model originated from Fick's second law in cylindrical coordinates and corrected the defect of the 2-D model. The refined diffusion model was expected to accurately model the diffusion test data to precisely determine the Phase I diffusivity of water vapor in the asphalt mixtures and to quantify the capability of moisture retention of the mixtures.

This paper is organized as follows. The next section describes the Phase I water vapor diffusion tests that were performed on two types of asphalt mixtures. The following section details the construction of the 3-D diffusion model, which was a closed-form formulation with infinite terms and two unknown parameters. The subsequent section presents the model fitting of the diffusion test data using the developed 3-D diffusion model; the number of terms in the diffusion model was determined so that the model was able to provide a satisfied level of model accuracy with a minimum number of terms to reduce computational efforts. The final section summarizes the major findings of this study and highlights the ongoing investigation of this topic.

2. Performance of water vapor diffusion tests

2.1. Preparation of asphalt mixture specimens

Two types of asphalt mixture specimens were prepared for the Phase I water vapor diffusion tests, including hot mix asphalt (HMA) specimens and fine aggregate mixture (FAM) specimens.

The same limestone aggregates were utilized to fabricate the HMA and FAM specimens. The aggregate gradation of the HMA specimens is presented in Table 1. The FAM specimens had aggregate particles passing the No. 16 sieve with an opening of 1.18 mm. The proportion of the aggregates with different sizes in an FAM specimen was exactly the same as that of the aggregates passing the No. 16 sieve in an HMA specimen. Table 2 exhibits the aggregate gradation of the FAM specimens. All HMA and FAM specimens were fabricated using the same #70 petroleum asphalt binder (graded based on the penetration) modified with the styrene-butadienestyrene (SBS) modifier. The optimum binder contents for the HMA specimens and the FAM specimens were determined to be 4.3% and 11.3%, respectively.

Each batch of the loose mix was compacted into a raw specimen with a 150 mm diameter and 170 mm height using a Superpave gyratory compactor. Every raw specimen was then cored and cut into a standard specimen with a 100 mm diameter and 150 mm height. The air void contents of the standard HMA specimens were controlled at 4.3 ± 0.5%, while the standard FAM specimens had air void contents of 1.5 ± 0.5%. Subsequently, a slice with a 20 mm height was cut from the middle part of the standard specimen; the slice was then cored into test specimens with a 12 mm diameter. These geometric dimensions were selected for the test specimens so that each specimen had almost the largest size that our test equipment was able to accommodate. Figs. 1 and 2 illustrate the preparation of the HMA test specimens and FAM test specimens, respectively, for the Phase I water vapor diffusion tests.

2.2. Procedure for Phase I water vapor diffusion tests

A Gravimetric Sorption Analyzer (GSA) was employed to perform the Phase I water vapor diffusion tests. The configuration of the GSA is exhibited in Fig. 3. In every diffusion test, a test specimen was placed in the sample container inside the measuring cell. The magnetic suspension balance with a resolution of 0.01 mg continuously measured the weight of the test specimen. The test temperature was controlled at 20 ± 0.5 °C.

As the test started, a high vacuum (<0.1 mbar) was applied to the measuring cell for about 20 h until the weight of the test specimen remained unchanged, which indicated that the RH of the specimen reached approximately 0%. The measured weight of the specimen at RH = 0% was taken as the initial weight of the specimen, which was denoted as M_0.

Subsequently, the vapor pressure cell generated water vapor at a pre-set pressure level of 12 mbar. The vapor dosing valve was then opened to allow the generated water vapor to enter the measuring cell to form a constant vapor pressure of 12 mbar. Since the saturated water vapor pressure was 23.298 mbar at 20 °C, the RH level inside the measuring cell was maintained at 51.51% (=12 mbar/23.298 mbar) throughout the test. Because of the RH differential between the inside and the outside of the test specimen, water vapor molecules continuously diffused into the specimen, which resulted in the weight increase of the specimen. The

Table 1
Aggregate gradation of HMA specimens.

Sieve Size (mm)	26.5	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	<0.075
Individual % Retained	0	2.2	8.3	11.4	23.7	19.8	11.6	4.2	5.1	4.2	2.4	1.6	5.5
Cumulative % Passing	100	97.8	89.5	78.1	54.4	34.6	23	18.8	13.7	9.5	7.1	5.5	0

Table 2
Aggregate gradation of FAM specimens.

Sieve Size (mm)	1.18	0.6	0.3	0.15	0.075	<0.075
Individual % Retained	0	27.13	20.74	14.36	8.51	29.26
Cumulative % Passing	100	72.87	52.13	37.77	29.26	0