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Water vapor diffusion in asphalt mixtures under different relative humidity differentials

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HIGHLIGHTS

- Performed water vapor diffusion tests in asphalt mixtures at different ΔRH.
- Derived rigorous physical model for water vapor diffusion in asphalt mixtures.
- Identified inverse proportionality between ΔRH and diffusivity in vapor pressure.
- Established a linear model between ΔRH and diffusivity in 1 atmosphere.
- Confirmed mixture anisotropy via diffusivities in axial and radial directions.

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ABSTRACT

It has been demonstrated that water vapor consistently transports in asphalt pavements. The relative humidity differential, which exists between the subgrade below and the atmosphere above the pavement, is a major contributor to the water vapor diffusion. However, the effect of the relative humidity differential has not been quantified on the water vapor diffusion in asphalt mixtures. This paper designed a laboratory experiment to investigate the water vapor diffusion in asphalt mixtures under a number of relative humidity differentials. The designed experiment consisted of five individual water vapor diffusion tests, each of which was performed at a specific relative humidity differential in the pre-vacuumed measuring cell of the test equipment. Two diffusion models were developed based on the Fick's second law of diffusion. It was found that the two-dimensional model provided an accurate characterization of the water vapor diffusion in both radial and axial directions of the cylindrical test specimens.

A linear model was established between the relative humidity differential and the total diffused mass based on the real gas law. An inverse proportionality was identified between the relative humidity differential and the diffusivity in both radial and axial directions. The determined diffusivity values were further converted to the corresponding diffusivity values under 1 atmosphere, which were in agreement with the diffusivity data reported in the literature. A linear model was derived for the relationship between the relative humidity differential and the diffusivity under 1 atmosphere, which indicated faster water vapor diffusion in asphalt pavements when subjected to a larger relative humidity differential between the subgrade and the atmosphere. The diffusivity in the radial direction was always larger than that in the axial direction despite the variation of the relative humidity differential. This fact implied the anisotropic distributions of air voids and aggregates in the asphalt mixture specimens, which assisted water vapor in diffusing more easily in the radial direction than in the axial direction.

1. Introduction

It has been demonstrated that water vapor consistently transports in asphalt pavements even with impermeable dense-graded asphalt layers [1–2]. A major contributor to the water vapor transport is the relative humidity differential that exits between the subgrade below the pavement structure and the atmosphere above the pavement. Since the total suction of the subgrade varies in the range from 2 to 4.5 pF [3–7], the relative humidity of subgrade is always above 98% according to the Kelvin equation [8]. Therefore, the dependably humid pavement subgrade and the atmosphere form a relative humidity gradient, which drives water vapor to

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migrate in the pavement structure. During this process, water molecules are brought into the asphalt layers and then debond the asphalt mixture, which leads to the moisture damage of the asphalt pavements. This mechanism explains the moisture damage of asphalt pavement sections in desert areas such as those identified in the State of Arizona, US [9]. In despite of the precipitation shortage in desert areas with an arid climate, the distinction in the relative humidity between the dry air and the humid subgrade provides high potential to water vapor for transporting in the pavement structure. This fact indicates that, even if the asphalt mixture is impermeable to liquid water, water vapor can still diffuse into the mixture so as to supply sufficient resources to trigger the moisture damage. As a result, water vapor transport in asphalt mixtures should certainly engage serious attention when investigating the moisture damage of asphalt pavements.

The observation of water vapor transporting in an asphalt mixture, which is practically impervious to liquid water, suggests that the diffusivity of water vapor in the asphalt mixture is significantly larger than that of liquid water. This suggestion has been confirmed in laboratory experiments that were conducted on asphalt binders, fine asphalt mixtures and full asphalt mixtures. The following findings of these laboratory experiments were reported:

1. In asphalt binders: the diffusivity of water vapor was measured to be in the order from 10^{-5} to 10^{-4} mm^2/s, while that of the liquid water was found to be in the order of 10^{-11} mm^2/s [10–14];
2. In fine asphalt mixtures: the water vapor had a diffusivity in the order from 10^{-5} to 10^{-4} mm^2/s [15–18], which was at least 100 times larger than the diffusivity of liquid water that was in the order of 10^{-7} mm^2/s [19,20];
3. In full asphalt mixtures: the diffusivity of water vapor was determined to be in the order from 10^{-4} to 10^{-3} mm^2/s [17,21].

All of these diffusivity data were determined under room temperature, 1 atmosphere and a constant relative humidity differential. The effect of the relative humidity differential has not yet been quantified on the water vapor diffusion in asphalt mixtures.

To address this research need, this study investigated the diffusion of water vapor in asphalt mixtures under a variety of relative humidity differentials. The diffused water vapor mass was measured continuously and the diffusivity was determined at each relative humidity differential. The next section describes the design and procedure of the water vapor diffusion experiment under different relative humidity differentials. The subsequent two sections present the one-dimensional (1-D) and two-dimensional (2-D) diffusion models, respectively, that were developed according to the specific experimental design in this study based on the fundamental diffusion theory. The succeeding section discusses the effect of the relative humidity differential on the total diffused mass and the diffusivity of water vapor. The following section then illustrates the conversion of the diffusivity values measured under water vapor pressure only to the diffusivity under 1 atmosphere, the characteristics of which are also detailed in this section. The final section summarizes the major findings of this study.

2. Design and procedure of water vapor diffusion experiment

Since the general diffusivity of water vapor in asphalt mixtures is in the order of 10^{-3} mm^2/sec or even smaller (as presented in Introduction), it would take enormous amount of time to acquire sufficient test data if performing the diffusion experiments under 1 atmosphere. To expedite the diffusion process so as to shorten the test duration, the Gravimetric Sorption Analyzer (GSA) apparatus was employed to perform the diffusion tests in its pre-vacuumed measuring cell so that only water vapor pressure was imposed on the asphalt mixture specimen. The specific experimental design and procedure are detailed as follows.

2.1. Specimen preparation

The asphalt mixture specimens were made of limestone aggregates produced in Hubei Province, China, and an asphalt binder modified with the styrene-butadiene-styrene (SBS) modifier. The Superpave Gyrator Compactor was used to compact each batch of the asphalt mixture into a raw specimen 150 mm in diameter and 170 mm in height, as shown in Fig. 1a. The raw specimen was then cored and cut to a standard specimen 100 mm in diameter and 150 mm in height, as presented in Fig. 1b, for the purpose of achieving a more uniform air void distribution in the specimen. The air void content in the specimen was controlled at 4.3% ± 0.5%.

Because of the space limit of the measuring cell of the GSA, the standard specimen was cut to thin slices with a thickness of 20 mm, as illustrated in Fig. 1c. Each slice was then cored to obtain smaller cylindrical specimens (see Fig. 1d), which were the test specimens for the water vapor diffusion experiments. Each test specimen had a size of 12 mm in diameter and 20 mm in height, which was almost the largest size that the measuring cell could accommodate.

2.2. Test configuration

The test equipment GSA, as shown in Fig. 2a, was custom-made to perform the water vapor diffusion test at a variety of relative humidity differentials in terms of water vapor pressures. A major advantage of this equipment was that the diffusion tests could be performed in a pre-vacummed measuring cell so that the diffusion process could be expedited significantly. Fig. 2b illustrates the internal configuration of the GSA, in which the chamber under the "Magnetic Suspension Balance" on the left is the measuring cell. Double-walled thermostatic jackets fit exactly around the measuring cell to prohibit the heat transfer between the cell and the laboratory atmosphere. Accordingly, the measuring cell can provide precise and steady test temperatures in the range from 0 °C to 150 °C. Fig. 2c presents a more detailed illustration of the measuring cell.

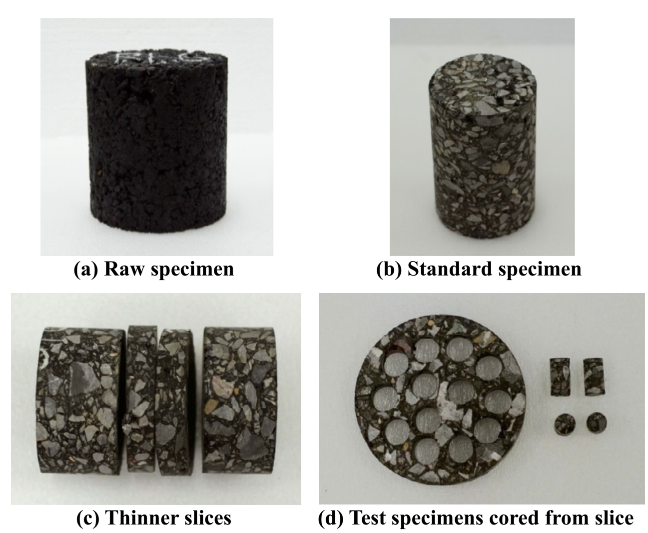

Fig. 1. Preparation of test specimens for water vapor diffusion experiment.