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Determination of oxygen diffusion coefficients of compacted asphalt mixtures

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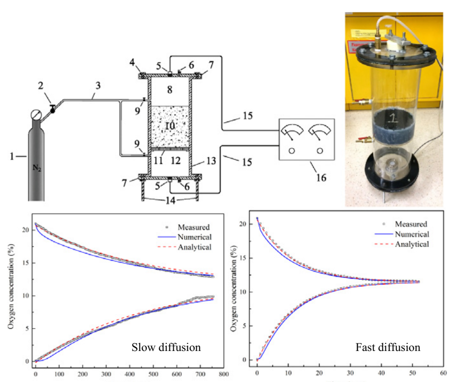
HIGHLIGHTS

- The oxygen diffusion coefficients (Ds) of compacted asphalt mixtures are determined.
- Ds of different asphalt mixtures vary in orders of magnitude.
- Ds of asphalt mixtures affect their aging susceptibility.
- Ds estimation models for dry porous media do not fit for asphalt mixtures.
- Ds of asphalt mixtures depend on air voids and other volumetric characteristics.

GRAPHICAL ABSTRACT



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ABSTRACT

The oxidative aging of asphalt binder in asphalt mixture is a key factor that affects the long-term durability of asphalt pavement. The aging susceptibility of an asphalt mixture is dependent on oxygen transport and consumption in the mixture. In this study, an apparatus was developed to measure oxygen diffusion and consumption in compacted asphalt mixtures, and methods to compute oxygen diffusion and possible consumption of asphalt mixtures were evaluated and compared. Oxygen diffusion coefficients of samples prepared with different asphalt mixture designs and air void contents were determined, and correlations between the diffusion coefficients and samples' volumetric characteristics were examined. The oxygen environment exposed by asphalt binders in pavements and its implication on pavement durability were also discussed based on simulated oxygen concentration profiles with time. The developed apparatus and test procedure were found to be suitable to measure the oxygen diffusion coefficients of compacted asphalt mixtures. It was also found that oxygen consumption during the diffusion test at room temperature is negligible, and both numerical and analytical methods perform equally well in calculating oxygen diffusion coefficients. The oxygen diffusion coefficients of the tested asphalt samples vary in orders of magnitude, dependent not only on air void contents but also on other volumetric characteristics. The traditional models to predict the oxygen diffusion coefficients of dry porous media are not fit for compacted asphalt mixtures. The oxygen diffusion coefficients of asphalt mixtures have significant implications on oxygen level exposed by asphalt binders inside of the pavements; therefore, they may be used as an indicator in asphalt mixture design and construction quality control.

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1. Introduction

Asphalt mixture is a widely used material for the construction of road, airfield, and parking lot pavements. The aging of asphalt binders in asphalt mixtures creates profound impacts on nearly all the critical performance-related properties of asphalt mixtures. In particular, aged asphalt binders become stiffer and more brittle, leading to higher asphalt stress and making pavements more susceptible to cracking under a given deformation [1–3]. Because asphalt binder aging is a key issue for asphalt pavements, it has been a subject of study for nearly one hundred years [4].

Compared to prolific literature on asphalt binder aging, asphalt mixture aging receives much less attention. A comprehensive literature review by Glover et al. [5] suggests that research to consider oxygen transport into hot-mix asphalt (HMA) mixture as well as into asphalt binder in the mixture is "practically nonexistent." The finding is echoed by another comprehensive review by Petersen [6], who believes that "The pragmatic importance of differential oxidative age hardening as a function of pavement depth to pavement service life ...... is self evident" and more understanding is demanded.

The existing limited number of investigations on the aging issues of compacted asphalt mixtures are mainly based on experiences gained from field. Early studies suggest that the oxidative aging of asphalt binder primarily occurs at asphalt pavement surface (less than 40 mm) [7,8]. These findings have significant influences on pavement research and practices and have been incorporated into the global aging model of the Mechanistic-empirical Pavement Design Guide (ME-PDG) [5]. More recent studies in Texas, USA, however, suggest that asphalt aging may penetrate into deeper HMA pavement layers [9]. Using binder test data obtained at various times from a heavily trafficked 36 year-old HMA pavement, researchers in another study examined the evolution of asphalt binder aging as well as the variations of aging severity with pavement depth [3]. The study found that asphalt binder continuously and severely ages over time in the asphalt pavement, regardless of its location in the pavement structure. Test data also revealed that mixture type and pavement depth have statistically significant impacts on binder aging [3]. Therefore, the assessment of aging susceptibility of asphalt mixtures and development of more aging-resistant mixtures are the key to improve asphalt pavement durability.

In a compacted asphalt mixture, the aging susceptibility of a particular asphalt binder is influenced by temperature and oxygen accessibility of the binder. One easily conceivable approach to assessing the aging susceptibility of compacted asphalt mixture is to examine its total air void content [5]. Although total air void content provides some indication on the oxygen accessibility of asphalt binder, it does not provide information on the connectivity of the air voids. After all, oxygen diffuses much slower through asphalt binder and aggregate than through those interconnected air void channels. Recently, a research team led by Glover [5] made several investigations on this issue, and they used X-ray computed tomography (CT) to examine air void characteristics. Although those studies on oxygen transport and diffusion at the microscopic level help advance our understanding on binder aging phenomenon in asphalt mixtures, the reliance on CT images creates several limits. Firstly, the resolution of CT images is usually inadequate to detect small air voids and air void channels [10]. Secondly, computer programs for accurately calculating air void content and connectivity still need to be improved [11]. Thirdly, many pavement practitioners do not have access to CT facilities; therefore, they may not be able to use this technology to assess the aging susceptibility of compacted asphalt mixtures.

To address the limits, this research was focused on oxygen diffusion and consumption in bulk compacted asphalt mixture as an entirety. The microscopic details of air void sizes and distributions are not needed. An apparatus to measure oxygen diffusion and consumption in compacted asphalt mixtures was developed, and methods to compute oxygen diffusion coefficients and possible oxygen consumption rates of the asphalt mixtures were evaluated and compared. Based on our best knowledge, this is the first time that this approach is used to assess oxygen transport efficiency in compacted asphalt mixtures. The derived oxygen diffusion coefficients may provide useful indications on the aging susceptibility of asphalt mixtures. The rest of the paper is organized as follows. In Section 2, the developed apparatus as well as the computational methods are introduced. In Section 3, examples of using the developed apparatus are illustrated and the results are analyzed. In Section 4, summary and conclusions are made. It is believed that the developed approach provides a convenient way to assess the aging susceptibility of asphalt mixtures, thereby contributing to the development of more durable asphalt mixture designs and quality control criteria in the future.

2. The measurement equipment, procedure, and computational methods

2.1. The measurement equipment and procedure

The concept of oxygen diffusion and consumption in asphalt mixture through the interconnected air paths is shown in Fig. 1. Oxygen in the atmosphere enters asphalt mixture through the surface openings, or through the bottom openings if the air in pavement granular base or subbase has an oxygen level higher than that in the air inside of asphalt mixture. Oxygen diffuses rapidly in the interconnected air voids, but very slowly in asphalt binder and aggregate. As oxygen diffuses into asphalt binder, it reacts with the aromatic, resin, and asphaltene components in the binder. The oxidative aging process consumes oxygen. However, because the oxidative aging rate of asphalt binder at room temperature is slow and binder content is typically only about 4–6% of the total

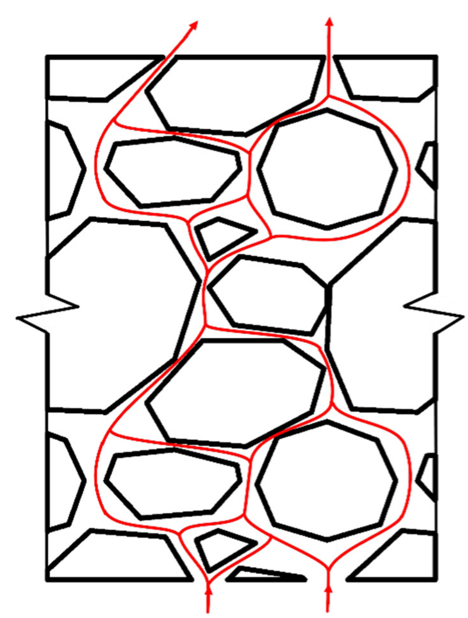

Fig. 1. A schematic diagram of oxygen diffusion in compacted asphalt mixtures.