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Micro-scale moisture distribution and hydrologically active pores in partially saturated asphalt mixtures by X-ray computed tomography

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HIGHLIGHTS

- Quantify the moisture distribution under hydro-static and -dynamic loading by XCT.
- Clarify vehicle load impact on the microscale moisture distribution characteristic.
- Determine the pore size distribution-hydraulic parameter relation in asphalt mixes.
- Propose the hydrologically active pore sizes in partially saturated asphalt mixes.

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ABSTRACT

Moisture distribution is the cause of premature deterioration in asphalt mixtures. However, quantifying of complex moisture distributions and their relationships to hydraulic loading patterns and pore structure remain challenging. This study is aimed to (1) quantify 2D moisture distribution within the pore structure of asphalt mixtures using X-ray computed tomography, and to (2) investigate the hydrologically active pore characteristics related to various hydraulic loadings in asphalt mixtures. A dense-graded asphalt mixture with a maximum aggregate size of 13.2 mm was prepared in the laboratory. X-ray computed tomography technology was used to capture moisture distribution within samples under hydrostatic and hydrodynamic pressures. The characteristics of moisture distribution, including volumetric moisture content, degree of saturation, and void number were quantified by comparing pore structure before and after hydraulic action. Analysis of variance indicated that hydraulic loading pattern, hydraulic gradient, vehicular velocity, and vehicular loading significantly influenced moisture distribution characteristics. Within the same sample, the asphalt mixtures under hydrodynamic pressure had lower void number and greater volumetric moisture content/saturation degrees than those under hydrostatic pressure, especially with higher loading frequency and amplitude, indicating that vehicular loading action aggravates moisture infiltration into pavement and increases the possibility of moisture damage. The hydrologically active pore structure was also analyzed using moisture distribution characteristics under varied levels of hydrostatic/hydrodynamic pressure. Interestingly, the hydrologically active pore sizes of asphalt mixtures under various hydraulic pressures differ from each other and provide various flow pathways for moisture transport, leading to the diversity of moisture distributions. These results provide a quantitative evaluation of microscale moisture distribution characteristics in asphalt mixtures, and these characteristics have significant implications for moisture transport modeling and moisture-induced damage prediction in field asphalt pavement.

1. Introduction

The importance of moisture distribution in asphalt pavements resulting from the exposure to the natural environment has been widely recognized. During the past 20 years, the interest in this issue has increased because of the attention to the moisture-induced damage in the early service life of pavements, such as striping, permeant deformation, and cracking [1–4]. However, moisture distribution characteristics in asphalt mixtures are still a challenge in pavement engineering.

Research on moisture distribution in asphalt pavements started in the early stage of the last century and developed with the

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progress of flow mechanism in porous medium. In 1856, Darcy derived a linear phenomenological equation to depict the moisture discharge velocity through a porous medium to the hydraulic gradient according to the continuum-based homogeneous domain theory [5]. McLaughlin and Goetz [6], and Zube [7] introduced Darcy's law into the development of test methods for macro-scale moisture distribution on either lab-prepared samples or field cores. With these developed methods, researchers illustrated the effects of voids, aggregate gradation, freeze-thaw cycles, lift thickness, and binder creep on moisture transport through asphalt mixtures [8–11]. Moreover, numerous entirely empirical and semi-theoretical equations have been derived to describe the mathematical relationship between the critical influences and the experimentally determined hydraulic properties [12]. However, stochastic distribution of aggregates, heterogeneities in the void structure, and widespread micro-fractures cause asphalt mixtures to deviate significantly from the continuum assumption. Furthermore, asphalt mixture is not similar to a continuum material [13–15]; instead, it owns heterogeneities with discrete flow paths embedded into it [16]. Recent studies have pointed out that preferential flow exists in asphalt mixture [17,18]. Contrary to the classical continuum assumption that fluid in an asphalt mixture is distributed throughout – and completely fills – the voids, water within the void space in asphalt mixture is rarely uniform and seldom completely fills the space. Thus, a necessary shift from a continuum-based method to a micro-scale network-oriented framework is required for a deep and detailed understanding of moisture distribution in asphalt mixtures.

Moisture distribution in the pore structure of asphalt mixtures is difficult to characterize by only traditional tests, which usually involve inserting a transducer into the region of interest. Advanced technologies, such as nuclear magnetic resonance and micro-focus X-ray computed tomography (CT), provide an opportunity to describe micro-level pore structures. Using the micro-scale imaging, numerous studies have been conducted to simulate flow transport and distribution within the microstructure of asphalt mixtures. Al-Omari and Masad [19] simulated steady fluid flow in the 3D pore structure of an asphalt mixture using the data set of 2D images and discussed the sensitivity of calculated permeability on the spatial image resolution. Using the Lattice-Boltzmann method, Kutay et al. [20,21] and Umiliaco et al. [22] developed a 3D moisture transport model using micro-scale images to describe the unsteady moisture flow in asphalt pavements under hydrodynamic/hydrostatic loading and illustrated the transverse anisotropy characteristic of water movement. But meanwhile, Poulikakos [23] and Vardanega [16] clearly asked for experimental data capable of certifying these micro-scale simulation results. The quantitative experimental results of micro-scale moisture distribution enable our understanding of the linkage between the pore structure of asphalt mixtures and real-time flow dynamics under hydrostatic and hydrodynamic pressures. However, little information can be drawn from the presently available literature.

In recent years, microstructure detection technique has quantified the pore-network and fluid flow in porous medium, promoting the micro-scale analysis of moisture distribution in soil and cracked rocks [24,25]. Coles and his co-workers [26] initiated the use of X-ray CT to describe liquid phase distribution in rock matrices. Using this measuring method, the potential for moisture movement and distribution in soil and rock has been associated with the initial volumetric moisture content [27], macro-pore characteristics [28], degree of soil structure [29], vegetative cover variability [30], and clay/organic matter content [31]. Moreover, the active regions related to moisture movement in soil were preliminarily identified, and the geometric properties of the active structure network were drawn from the entire structure [32–34]. Particularly, available reference for preferential flow and active structure network in soil and rock using X-ray CT provides technical guidance for analyzing micro-scale moisture transport and hydrologically active pores in asphalt mixtures. Khan et al. [35] firstly introduced this technique into the quantitative analysis of moisture distribution in the pore structure of asphalt mixtures. Xu et al. [36] discussed the expansion of flow paths under freeze-thaw cycles in asphalt mixtures by X-ray CT images, providing a foundation for determination of hydrologically active pores in asphalt pavement.

In conclusion, in the available literature, detailed information on the micro-scale moisture distribution in asphalt mixtures is rare. Existing studies paid limited attention to model the moisture flow using numerical simulation method according to the homogeneous domain theory, but the observed micro-scale moisture distribution characteristics in asphalt mixtures, which are heterogeneous with discrete flow networks, have not yet been addressed. However, in the discussion of preferential flow in structured soil and rocks, X-ray CT is a reliable tool to quantify the non-equilibrium flow in soil and rocks [28–31,33], and is helpful for investigating the moisture distribution in pore structure of asphalt mixtures.

In the present study, the objectives were to (1) quantify 2D moisture distribution within the pore structure of asphalt mixtures using X-ray CT, and to (2) investigate the hydraulic active pore characteristics related to various hydraulic loading in asphalt mixtures. An X-ray Microscopic CT Scanner was used to examine the micro-scale moisture distribution in asphalt mixtures. Moisture distribution characteristics, including volumetric moisture content, degree of saturation, and void number, were quantitatively determined along the depth with various hydraulic loadings. A comparative analysis of the moisture distribution characteristics, with emphasis on the impact of hydraulic loading patterns, was conducted, and the role of dynamic vehicular loading was defined. Moreover, we related moisture distribution to the pore structure of asphalt mixtures using statistical analysis, and the hydrologically active pore sizes for moisture transport in asphalt mixtures under different hydraulic loading were proposed.

2. Experimental program

2.1. The asphalt mixture studied

A polymer modified asphalt with a penetration grade of 60/80 and a tuff aggregate with a silica content of 54.9% were used for specimen preparation. The modified asphalt was obtained from Northeast Refining and Chemical Engineering Co., Ltd. The aggregate material was supplied by an aggregate processing plant in Heilongjiang Province.

Due to the difficulty to capture the fast-moving moisture flow in open graded friction courses by X-ray CT [37] and the severe moisture induced damage observed in dense graded mixtures [3,38], a type of dense graded mixture with a maximum aggregate size of 13.2 mm was selected for this study. The commonly used proportion of the constituent materials (coarse aggregate, fine aggregate, mineral filler, and asphalt binder) of asphalt mixtures in China was 60: 29: 6: 5 by weight. As suggested by Masad et al. [13] and Coenen et al. [39], the Superpave gyratory compactor (SGC) most accurately reproduces the pore structure as that in the field. Therefore, the sample was compacted at 170 °C using SGC with an gyration angle of 1.25 °C and vertical pressure stress of 0.6 MPa. The target volumetric void content is 5% following Technical Specifications for Construction of Highway Asphalt Pavements in China (JTG F40-2004). A total of 8 replicate samples were prepared to demonstrate the moisture distribution characteristics under various hydraulic pressures.