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X-ray computed tomography in hydraulics of asphalt mixtures: Procedure, accuracy, and application

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HIGHLIGHTS

- Evaluate the feasibility to examine hydraulics of asphalt concrete (AC) by X-ray CT.
- Discuss factors that affect the accuracy of X-ray CT on hydraulics of AC.
- Propose optimal test conditions for analyzing hydraulics of AC using X-ray CT images.
- Determine the moisture distributions in micro-scale of AC under dynamic loading.

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ABSTRACT

A combination of advances both with respect to experimental techniques as well as image processing procedures accurately describes moisture distribution in the internal structure of asphalt mixtures using X-ray computed tomography technology. The quantitative and qualitative X-ray CT results for partially saturated asphalt mixtures are displayed, which is obtained with different test parameters of X-ray CT and sample sizes to demonstrate the effect of these parameters on measurement accuracy of the hydraulics of asphalt mixtures using X-ray CT images, considering the aspects of both image resolution and contrast. In addition, we present several applications of our two-dimensional X-ray CT images before and after saturation, which analyzes the moisture distribution in the micro-scale of asphalt mixtures with various loading sizes and speed. This method provides an effective opportunity to reveal the dynamic/static water distribution characteristics on the micro-scale of asphalt mixtures and verify various numerical modeling methods.

1. Introduction

Water in asphalt pavements negatively affects its performance and results in moisture distress primarily by damaging the adhesive bond at the aggregate–asphalt binder interface [1–3]. Moisture damage is associated with stripping, permanent deformation and excessive deflections. Therefore, moisture damage begins from moisture transport and distribution in asphalt mixtures. Knowledge of moisture transport and distribution in asphalt mixtures will aid in understanding distresses caused by infiltration of moisture within asphalt pavement.

Difficulties associated with the quantitative measurements of internal structure in asphalt mixtures have hindered discussions on the macro-scale moisture flow. Cooley et al. [4] and Zube [5] considered asphalt mixtures homogeneous materials. Darcy's law was employed in describing the moisture distribution in asphalt mixtures [6,7]. Macro-pore is clearly asserted as a crucial factor for accelerated breakthrough of moisture [8–10]. However, asphalt mixtures with the same macro-pore may have diverse air void distributions. Consequently, they perform a distinct ability to transport moisture. Hence, to fully understand the significance of moisture distribution, as well as diffusion processes, high priority is given to micro-scale analysis.

Micro-scale analysis is difficult to develop using only traditional measurement techniques, which usually plug a sensor at the region of interest. Advanced technologies, such as X-ray computed tomography (CT), allow porous medium to be characterized based on their micro-level structure distribution. By using pore-scale images, researchers have conducted extensive studies on simulating moisture distribution in the internal structure of asphalt mixtures. Shakiba et al. [11] and Al-Omari and Masad [12] developed a numerical scheme to simulate moisture flow using X-ray CT images and analytically showed that air void distribution affects

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moisture distribution in pore structure of asphalt mixtures. Kutay and Aydilek [13] combined lattice-Boltzmann moisture model with X-ray images to investigate the horizontal and vertical components of moisture distribution in asphalt mixtures. Masad et al. [14] modeled non-uniform flow fields in different vertical location in asphalt mixtures. Based on three-dimensional digital images captured by X-ray CT, Arambula et al. [15,16] estimated the moisture vapor diffusion coefficient of asphalt mixtures in steady-state conditions via finite element method. Bhargava et al. [17] utilized a simple numerical scheme and cross-sectional images to discuss active pore size and length of flow channels in the asphalt mixtures. Benedetto and Umiliaco [18] simulated the unsteady flow of moisture through open-graded asphalt mixtures and discussed water velocity vectors at different pore structures. Simultaneously, Vardanega [19] and Masad et al. [20] specifically called for measurement techniques capable of certifying these numerical simulations. The ability to quantify water distribution in pore structure and transport in micro-scale enables quantitative analysis of theoretical and numerical modeling approaches. At present, little information can be obtained from existing literature.

Furthermore, X-ray CT is widely used to measure hydraulic properties within porous mediums, such as soil and rock systems. Application of this technique has previously demonstrated excellent measurements of moisture distribution and transport at the micro-scale. Coles et al. [21] introduced synchrotron X-ray micro tomography to identify oil and brine phases in rock matrix. Using this measuring method, experimental data were compared with simulation results and indicated good agreement. Wildenschild et al. [22] and Quinton et al. [23] analyzed the moisture content obtained with different scanning systems to demonstrate the important role of systems, spatial resolutions and contrast on the calculation accuracy of the hydraulics of soil, and derived their flow properties from image analysis. Luo et al. [24] combined X-ray CT technique and tracer method to study the point specific breakthrough curves and depicted preferential flow pathways in soil. Aravena et al. [25] evaluated the effects of root-induced compaction on the hydraulics of soil by using X-ray CT images, and illustrated the moisture flow increase around the root caused by root-induced deformation. With micro tomographic data, opportunities therefore exist to significantly affect the description and understanding of moisture transport and distribution properties within a porous medium.

In conclusion, for micro-scale moisture distribution and transport in asphalt mixtures, most efforts in the open literature aimed at modeling fluid flow in X-ray CT images of real asphalt mixture microstructure using numerical simulation. Few studies emphasized the effort of measurement technique. However, in the moisture transport in porous medium aspect, the availability of X-ray CT provides an opportunity to experimentally evaluate the micro-scale flow characteristic in porous medium, such as soils and rocks. The flow mechanism and preferential flow features have been clearly explained, which promotes the development of porous flow theory and numerical model.

In the present study, an X-ray CT test system with a spatial resolution of 5–40 μm is adopted into analysis. Depending on the system, the feasibility of use of X-ray CT to examine moisture distribution in asphalt mixtures is evaluated. A set of procedures for extracting and verifying micro-scale moisture distribution were established by comparing X-ray images before and after saturation. Then, a comparative analysis of measurement accuracy with emphasis on the effect of test conditions is offered, and optimal test conditions are proposed. Based on the optimized test conditions, micro-scale moisture distribution is quantitatively determined under various dynamic loading using 2D images of asphalt mixtures. The overall objective is to present a guideline for researchers in utilizing X-ray CT technique, selecting sample sizes and test conditions, to experimentally examine fluid flow in micro-scale.

2. Materials and methods

2.1. The asphalt mixtures studied

Asphalt binder 60/80 penetration grade and andesite type aggregate were adopted for sample preparation. The asphalt binder was supplied by China National Petroleum Corporation. Three types of mixtures were designed for analysis including a dense-graded asphalt mixture (AC), a stone mastic asphalt mixture (SMA), and an open-graded asphalt mixture (OGFC). Lignin fibers supplied by ZL Limited, Beijing, were used in SMA and OGFC with 3‰ by total mixture weight. Nominal maximum aggregate sizes for all asphalt mixtures were 13.2 mm.

A total of 27 samples of the three mixture types were prepared for comparison with a height of 63.5 mm and three different sample diameters (50 mm, 100 mm, and 150 mm) using Superpave gyratory compactor. Three replicate samples were fabricated for each combination of sample size and mixture type. The compaction effort applied on the sample was controlled with an angle gyration of 1.25°, vertical pressure stress of 0.6 MPa, and gyration speed of 30 rpm. For AC and SMA asphalt mixtures, samples were fabricated to achieve 4% target air voids content. For OGFC asphalt mixtures, the target air voids content was set to be 20%. Details of the aggregate gradations are summarized in Fig. 1.

2.2. Experimental procedure

In this study, an X-ray CT and a vacuum water tank were used in analysis. The vacuum water tank is used to push water into the asphalt mixtures by negative pressure. The maximum negative pressure of vacuum water tank is 3.5 kPa, which is equivalent to 27.5 mm of mercury. The X-ray CT unit (Phoenix v |tome| × s) is a tool to capture the internal structure of asphalt mixture under different moisture saturation conditions.

This X-ray CT unit is a scanner in which the X-ray source and detector are fixed and the tested sample rotates. This system has a 240 kV micro-focus X-ray generator and the maximum resolution is approximately 5 μm. The specimen is rotated 360° to receive radiation beam as the detector outputs intensity distribution images to the acquisition system. The intensity scale depends on the density and size of component materials. For asphalt mixtures, air voids occupy the lower part of the intensity scale because they have lighter weights than aggregates and asphalt mortar. High-density aggregates are at the highest intensity part, whereas asphalt mortar falls in between. A complete rotation takes about 20–25 min, depending on the amount of images taken. In this experiment, up to 100 slices were acquired in one rotation with 1000 views.

Experimental procedures were developed to test moisture distribution in asphalt mixture. Before the saturation of samples for this experiment, all the samples were scanned in the X-ray CT to determine the initial void distribution in dry condition. The dry mass of sample is also determined. Then, samples were immersed into distilled water at 15 °C after scanning for initial void distribution using a negative pressure of 3.5 kPa for 15 min. The saturated samples with distilled water were scanned in the X-ray CT. All flow processes stopped during this 25-min time period. After scanning, the samples were taken out of water, then the wet mass was determined by weighting so that and the percentage saturation can be calculated. At the end of each test, partial saturated samples were dried in oven with the temperature of 40 °C for 72 h to evaporate the moisture in the internal structure and reused for other cases.

Moisture diffusion in the specimen will result in a change of internal structure properties. Thus, the moisture distribution in asphalt mixtures can be determined

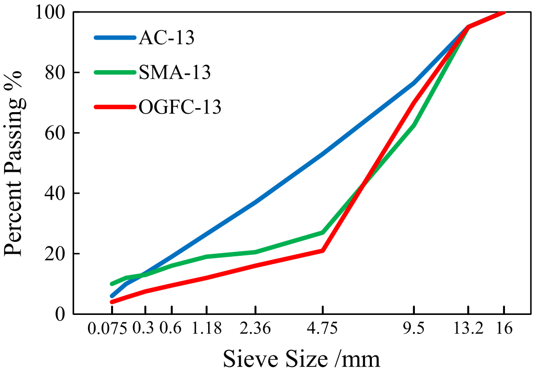

Fig. 1. Aggregate gradation curves for 3 types of asphalt mixtures.