Construction and Building Materials 158 (2018) 855–863

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Performance verification of various bulk density measurement methods for open- and gap-graded asphalt mixtures using X-ray computed tomography

Yuan Zhang [a], Zhen Leng [a,*], Zejiao Dong [b], Zhiyang Liu [b], Zeyu Zhang [a], Zhifei Tan [a]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, China

HIGHLIGHTS

- CT scanning images of asphalt mixtures acquired bimodal histograms of gray values.
- ISO50 threshold method determined boundaries between air voids and asphalt materials.
- Automatic vacuum sealing method worked both for open- and gap-graded asphalt mixtures.
- Parafilm coating method is suitable for gap-graded asphalt mixture.

ARTICLE INFO

Article history:
Received 29 July 2017
Received in revised form 24 September 2017
Accepted 19 October 2017

Keywords:
Open-graded asphalt mixture
Gap-graded asphalt mixture
Bulk density
Air void content
CT scanning

ABSTRACT

This paper presents a study aiming to verify the accuracies of various bulk density measurement methods for open-graded and gap-graded asphalt mixtures using X-ray Computed Tomography (CT) scanning. The industrial X-ray CT scanning was performed on laboratory prepared open-graded and gap-graded mixture specimens. The histograms of gray values from the CT scanning images showed distinct peaks of air voids and asphalt materials, based on which the threshold value for calculating the voxels of air voids was determined by the ISO50 threshold method. In this way, the actual air void contents of the testing specimens were determined successfully and then compared to the values calculated from the bulk densities measured using the selected methods, including the dimensional analysis, automatic vacuum sealing, Parafilm coating and saturated surface dry methods. The results from the statistical analyses showed that for the open-graded mixture, only the automatic vacuum sealing method produced air void contents, which were not significantly different from the CT scanning results. For the gap-graded mixture, neither the results from the automatic vacuum sealing method nor those from the Parafilm coating method showed significant difference compared with the CT scanning results.

1. Introduction

The increasing application of open-graded and gap-graded asphalt mixtures has created a need to identify the most accurate method to determine the bulk densities and/or air void contents of laboratory or field specimens made of these materials. Various studies [1–4] have reported that the conventional method, i.e., the saturated surface dry (SSD) method, may produce significant errors in bulk density measurement for open-graded and gap-graded asphalt mixtures. Compared to dense-graded asphalt mixture, the open-graded and gap-graded asphalt mixtures have rougher surface textures and higher percentages of interconnected air voids. That might cause quick infiltration of water into the testing specimen and drainage after removing it from water bath when the water displacement concept is applied to measure the volume of test specimen in the SSD method. An overestimated bulk density will be obtained in such situation. Some alternative methods, including the dimensional analysis, the Parafilm coating and the automatic vacuum sealing methods, have also been developed and used. In the dimensional analysis method, the bulk volume is calculated from the measured dimensions of a testing specimen. In the Parafilm coating method, the whole surface of a testing specimen is manually coated by the Parafilm to prevent water from penetrating into the specimen. Then, the water displacement concept is adopted to measure its bulk volume. In the

* Corresponding author.
E-mail address: zhen.leng@polyu.edu.hk (Z. Leng).

https://doi.org/10.1016/j.conbuildmat.2017.10.090
0950-0618/

last method, an automatic vacuum sealing device is used with a specially designed polymer bag to seal a testing specimen, allowing the use of water displacement concept for measuring the bulk volume.

However, all the aforementioned methods may produce different bulk densities and/or air void contents of the testing specimens, especially of those made with open-graded and gap-graded asphalt mixtures. Alvarez et al. [5] applied the dimensional analysis and automatic vacuum sealing methods to determine the air void contents of Permeable Friction Course (PFC), which is one typical open-graded asphalt mixture. It was found that higher air void contents were obtained from the dimensional analysis method compared with those from the automatic vacuum sealing method. King et al. [6] found that the automatic vacuum sealing method is more applicable for measuring the bulk densities of Open Graded Friction Course (OGFC) than the SSD method. Zhang et al. [7] used all three alternative methods to determine the air void contents of asphalt-treated permeable base. The automatic vacuum sealing method was concluded to be the most repeatable procedure with less variation than the other two methods, as evidenced by the lowest coefficient of variance and coefficient of repeatability. For Stone Matrix Asphalt (SMA), which is a typical gap-graded asphalt mixture, some bulk density measurement methods have also been compared and analyzed. Cooley Jr. et al. [8] found that the measured bulk densities of SMA by the automatic vacuum sealing method were smaller than those by the SSD method, and they were more accurate based on the hypothesis that a higher water absorption related to a lower measured bulk density. Rajagopal et al. [9] also found that the measured bulk densities using the automatic vacuum sealing method were lower than those determined using the SSD method. But the accuracy of the automatic vacuum sealing method was not discussed. In addition, some other researches on the coarse-graded mixtures [10–12] have reported that the automatic vacuum sealing method provides more accurate bulk density estimation than the SSD and dimensional analysis methods. However, in those previous studies, either the accuracies of the alternative methods were not discussed, or their accuracies were determined based on the comparison between the measured values and the designed/experience values or the coefficients of variance and repeatability of the measured values. This is because that the actual bulk densities or air void contents of the testing specimens were not available and none of these methods directly measure the real densities or air void contents of the testing specimens, resulting in the difficulty in determining the accuracies of the alternative methods.

This study aims to verify the accuracies of various bulk density measurement methods for open-graded and gap-graded asphalt mixtures using X-ray Computed Tomography (CT) scanning. The industrial X-ray CT scanning was performed on laboratory prepared open-graded and gap-graded mixture specimens to measure their actual air void contents. The bulk densities of these specimens measured by different selected methods were then used to calculate their air void contents and compared with the CT scanning results, so that the accuracies of these methods can be verified.

2. Volumetric analysis of asphalt mixture using CT scanning

In the analysis of CT scanning of asphalt mixtures, segmentation of the air voids, bituminous mortar and mineral aggregates highly depends on the threshold values for the CT scanning images. Thus, the threshold process is critical for extracting the volumetric properties of asphalt mixtures. At early stage, the resolution of CT scanning images of asphalt mixture specimens were quite low. The determination of threshold values mainly depended on the experiences with CT scanning images of asphalt mixtures. For instance, Masad et al. [13–15] and You et al. [16] selected the threshold values by means of adjusting the threshold values to match the material components based on visual inspection of the CT scanning images. With the wider application of CT scanning for asphalt mixtures, several threshold methods have been developed and applied to analyze the CT scanning images. One of these methods is to determine the threshold values by comparing the laboratory-measured volumetric properties of the testing specimens with the computer-calculated volumetric properties from CT scanning images. For instance, the threshold values for separating the air voids and mortar were adjusted based on the laboratory-measured air void contents [17–19]; and the threshold values for separating the mortar and aggregates were adjusted based on the laboratory-measured aggregate gradations [20–21]. Another method to determine the threshold values is the Otsu's threshold method [22–25], in which the CT scanning image is divided into two regions: the foreground and background. The foreground and background are composed of gray values greater and less than the threshold value, respectively. The optimum threshold value is the gray value that minimizes the within-class variances of foreground and background voxel classes. Finally, the threshold values can also be directly acquired from the histogram of gray values when there are distinct gray value peaks for the air voids, mortar and aggregates [26–28]. However, this only works for high-resolution CT scanning images, in which the gray intensity levels for the air voids, mortar and aggregates are significantly different from each other.

In the authors' previous studies [29,30], both the conventional medical CT scanner and high-resolution industrial CT scanner were used to scan the open-graded mixture specimens. Large specimens with a diameter of 150 mm were scanned with a resolution of $0.294 \times 0.294 \times 1.0$ mm using the conventional medical CT scanner. Small specimens with a diameter of 40 mm were scanned with a resolution of $0.04 \times 0.04 \times 0.04$ mm using the high-resolution industrial CT scanner. In the low-resolution CT scanning images (Fig. 1(a)), the boundaries between aggregates and mortar and between mortar and air voids are very fuzzy. In such situation, only a unimodal histogram of gray values can be obtained (Fig. 1(c)), in which one distinct peak where the distributions of gray intensity levels for different materials are concentrated in one particular range. However, the threshold values for the aggregates-mortar and mortar-air voids cannot be determined through the histogram of gray values. In the high-resolution CT scanning images (Fig. 1(b)), the boundaries between aggregates, mortar and air voids are relatively more clear than those in the low-resolution images. Since, three distinct peaks present in the histogram of gray values, in which the threshold values can be obtained directly (Fig. 1(d)). The air void contents of these testing specimens can be determined by calculating the number of voxels for the air voids and the total number of voxels for the whole specimen. However, the dimensions of these testing specimens are too small. Thus, the representability of their volumetric properties from the high-resolution CT scanning is in doubt. Theoretically, it is possible to scan a moderate-size specimen with such a high resolution. But this will require an advanced CT scanner. It will also create a big data and be very time-consuming. Therefore, CT scanning of moderate-size specimens with a moderate resolution, which allows direct determination of the threshold value for the air voids and asphalt materials from the histogram of gray values, will be ideal for this research.

3. Materials and measurements

3.1. Materials

In this research, the typical open-graded and gap-graded asphalt mixtures used in Hong Kong, i.e., Polymer Modified Friction Course (PMFC) and Polymer Modified Stone Mastic Asphalt (PMSMA), respectively, were investigated [31,32]. Table 1 pre-