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

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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.

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

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 inter-connected 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 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 0.294×0.294×1.0 mm using the conventional medical CT scanner. Small specimens with a diameter of 40 mm were scanned with a resolution of 0.04×0.04×0.04 mm using the high-resolution industrial CT scanner. In the low-resolution CT scanning images (Figure 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 (Figure 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 (Figure 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 (Figure 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.

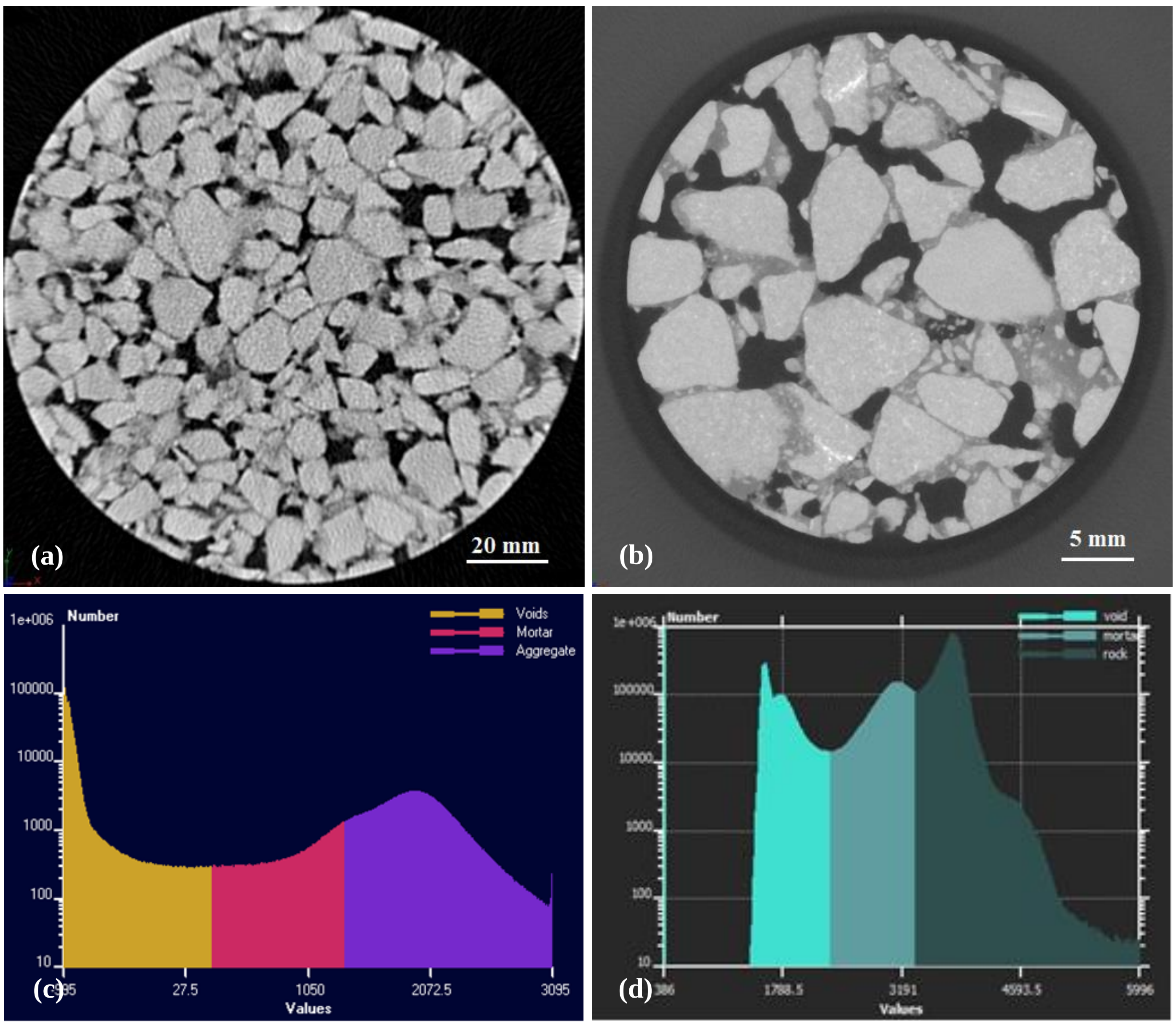

Fig. 1. Examples of CT scanning images of open-graded mixture specimens from the conventional medical CT scanner (a) and high-resolution industrial CT scanner (b), and their corresponding histograms of gray values (c) and (d).

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 presents the specified and designed material compositions for PMFC and PMSMA. It can be seen that both mixtures had a nominal maximum aggregate size of 10 mm. Local granite was used for the coarse and fine aggregates, while the mineral filler was also from granite rocks. The bitumen was a pre-blended type polymer modified bitumen that had a high temperature Superpave performance grade of PG 76 [33]. It is worth noting that low temperature performance grade is not required in Hong Kong because of the warm weather. The compaction standard for the PMFC mixture was 50 Marhsall hammer blows per side, while for the PMSMA mixture it was 75 blows per side. In total, seven PMFC specimens and seven PMSMA specimens were prepared for the bulk density measurements and CT scanning.

Table 1

Mixture design for the open-graded mixture PMFC and gap-graded mixture PMSMA.

Material	Sieve size [mm]	Apparent density [kg/m^3]	PMFC [% by mass pass]		PMSMA [% by mass pass]	
			specified	designed	specified	designed
Coarse aggregate	14	--	100	100	100	100
	10	2642	85-100	88	93-100	93
	5	2663	20-40	20	26-48	32
Fine aggregate	2.36	2709	5-15	11	21-35	27
	0.075	2649	2-6	4	9-14	10.4
Bitumen content	[% by total mass of mixture]		5.5-6.5	5.5	>6.0	6.2
Air void content	[% by total bulk volume]		>20	--	3.5~4.5	--

3.2. Measurements

After the Marshall specimens were prepared, X-ray CT scanning was first performed to measure their air void contents, followed by measurement of their bulk densities using different methods in the following order: dimensional analysis method, automatic vacuum sealing method, Parafilm coating method, and SSD method. Such arrangement was made to avoid the potential error associated with inadequate evaporation of water after the bulk density measurements using the water displacement concept, as only SSD method allows water to penetrate into the testing specimen.

The instrument used for the X-ray CT scanning is a phoenix v|tome|x s – industrial CT scanner. This scanner consists of a microfocus X-ray source, an object stage and a detector. During the scanning, the X-ray source and detector are fixed and the test specimen is rotating along the axial direction on the object stage. The X-ray CT scanning was conducted under the voltage of 180 kV and the current of 80 μA. A thin copper plate was placed between the X-ray source and the testing specimen as a filter to reduce the amount of lower energy component of X-ray spectrum. The resultant resolution is 0.109×0.109×0.109 mm. The 16-bit tiff images were exported from the X-ray CT scanning. These 16-bit images contain the information of voxels and gray values with a range of 0-65535, while the traditional 8-bit images only contain the information of pixels and gray values with a range of 0-255. The 16-bit images were processed using the commercial CT data analysis software VGStudio Max 3.0.0 from Volume Graphics. The image processing will be introduced in the next section.

The dimensional analysis method described in ASTM D3202 [34] was first used to determine the bulk densities of PMFC and PMSMA specimens after the X-ray CT scanning. Then the automatic vacuum sealing method was applied to measure the bulk densities of the specimens using the CoreLok system in accordance with ASTM D6752 [35]. The CoreLok system is a vacuum chamber that is used with specially designed polymer bags to completely seal the test specimens from water during the bulk density measurements [36]. Figure 2 (a) shows a picture of the automatic vacuum sealed specimen. After applying the automatic vacuum sealing method, the Parafilm coating method was utilized in accordance with ASTM D1188 [37]. Figure 2 (b) shows a picture of the Parafilm coated specimen as a reference. Finally, the SSD method was applied to measure the bulk densities and water absorptions of the PMFC and PMSMA specimens in accordance with ASTM D2726 [4].

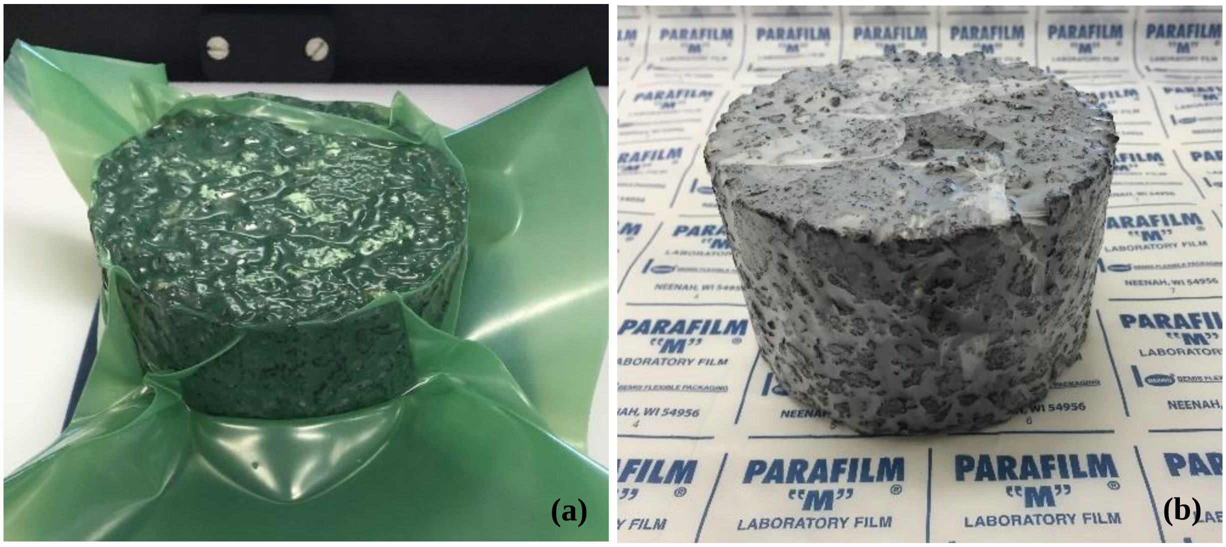

Fig. 2. Pictures of the automatic vacuum sealed specimen (a) and Parafilm coated specimen (b).

Besides, the theoretical maximum densities of the PMFC and PMSMA mixtures were measured separately according to ASTM D2041 [38]. The air void contents of the PMFC and PMSMA specimens were calculated from the measured bulk densities and theoretical maximum densities using the following equation:

$$Air\ void\ content = (1 - \frac{bulk\ density}{theoretical\ maximum\ density}) \times 100\% \quad (1)$$

4. Results and discussion

4.1. CT scanning image processing

The information derived from the CT scanning consists of voxel data in the scanning slices. Traditionally, the voxel data is converted into scatter plots or grids of triangles to analyze the component surface geometrically. But this conversion is very time-consuming and faces the risk of information loss. The commercial CT data analysis software VGStudio Max 3.0.0 from Volume Graphics can directly process the voxel data from the CT scanning, which eliminates the need for unnecessary data conversion [39]. In this research, the 16-bit images from CT scanning were first input into the VGStudio Max program and numerically reconstructed with a beam hardening correction. Even though during the CT scanning, a thin copper plate has already been placed between the X-ray source and the testing specimen to reduce the amount of lower energy component of X-ray spectrum to reduce the effect of beam hardening, it is very necessary to correct the beam hardening during the reconstruction. The main problem caused by the beam hardening is that it gives false information about the testing specimen's composition. It also negatively influences the results when a global threshold method is used to separate materials by intensity/gray value difference. After the reconstruction, the median filtering technique with a kernel size of 5×5 was applied to remove the image noise. From the filtered CT scanning images, a distinctly bimodal histogram of gray values was obtained for each scanned asphalt mixture specimen. Figure 3 shows a histogram of gray values from the CT scanning images of a PMFC specimen as an example. In the histogram, the air voids have a peak at lower levels of gray value while the asphalt materials have a peak at higher levels of gray value. In order to separate the air voids and asphalt materials in the CT scanning images, a threshold value needs to be selected from the bimodal histogram of gray values.

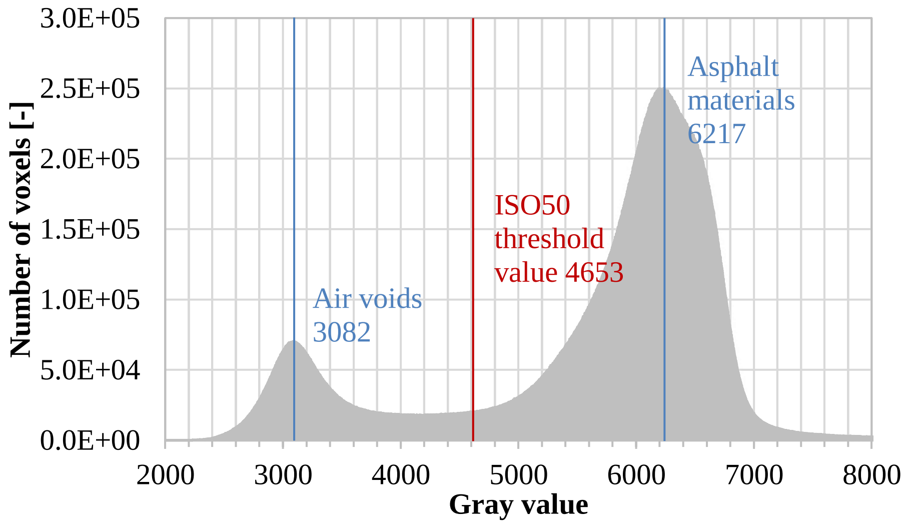

Fig. 3. Example of the histogram of gray values from the CT scanning images of a PMFC specimen.

From the histograms of gray values for all scanned specimens, it was found that the peak values of air voids for different scanned specimens are different, as well as their peak values of asphalt materials. This indicates that a different threshold value should be determined for each scanned specimen. The ISO50 threshold method within the "surface determination" function of the VGStudio Max program was implemented to determine the threshold values. The ISO50 threshold is the bisecting gray value point located at the center of the evaluated background (i.e., air voids) peak and material (i.e., asphalt materials) peak in the bimodal histogram (Figure 3). It has been reported that the ISO50 threshold method leads to better segmentation results compared to other threshold methods (e.g., Otsu's threshold method mentioned in the previous section) [40, 41]. Table 2 presents the threshold values for all scanned specimens.

Once the threshold values were determined, the voxels in the CT scanning images were segmented for the air voids and asphalt materials. The voxels with gray values lower than the threshold value belong to the air voids, whilst the voxels with gray values higher than the threshold value belong to the asphalt materials Figure 4 shows the examples of 3D visualization and 2D diametrical cross-sectional CT scanning images of PMFC specimen. Figure 4 (a) and (c) are images before the segmentation. By means of filling the air-void voxels with green color, the segmentation of air voids and asphalt materials is visible in the CT scanning images, as shown in Figure 4 (b) and (d). By comparing the images before and after the segmentation for all scanned specimens, it was found that the air voids were accurately detected in the colored images. This indicates that the threshold values determined using the ISO50 threshold method are appropriate for the CT scanning images of PMFC specimens.

In addition, it was found that there were relatively large percentages of inter-connected air voids in the PMFC specimens. So it can be expected that water can quickly infiltrate into the PMFC specimens and drain fast after removing the specimens from water bath when the SSD method is used for measuring the bulk density. This certainly causes an overestimated bulk density for PMFC specimens.

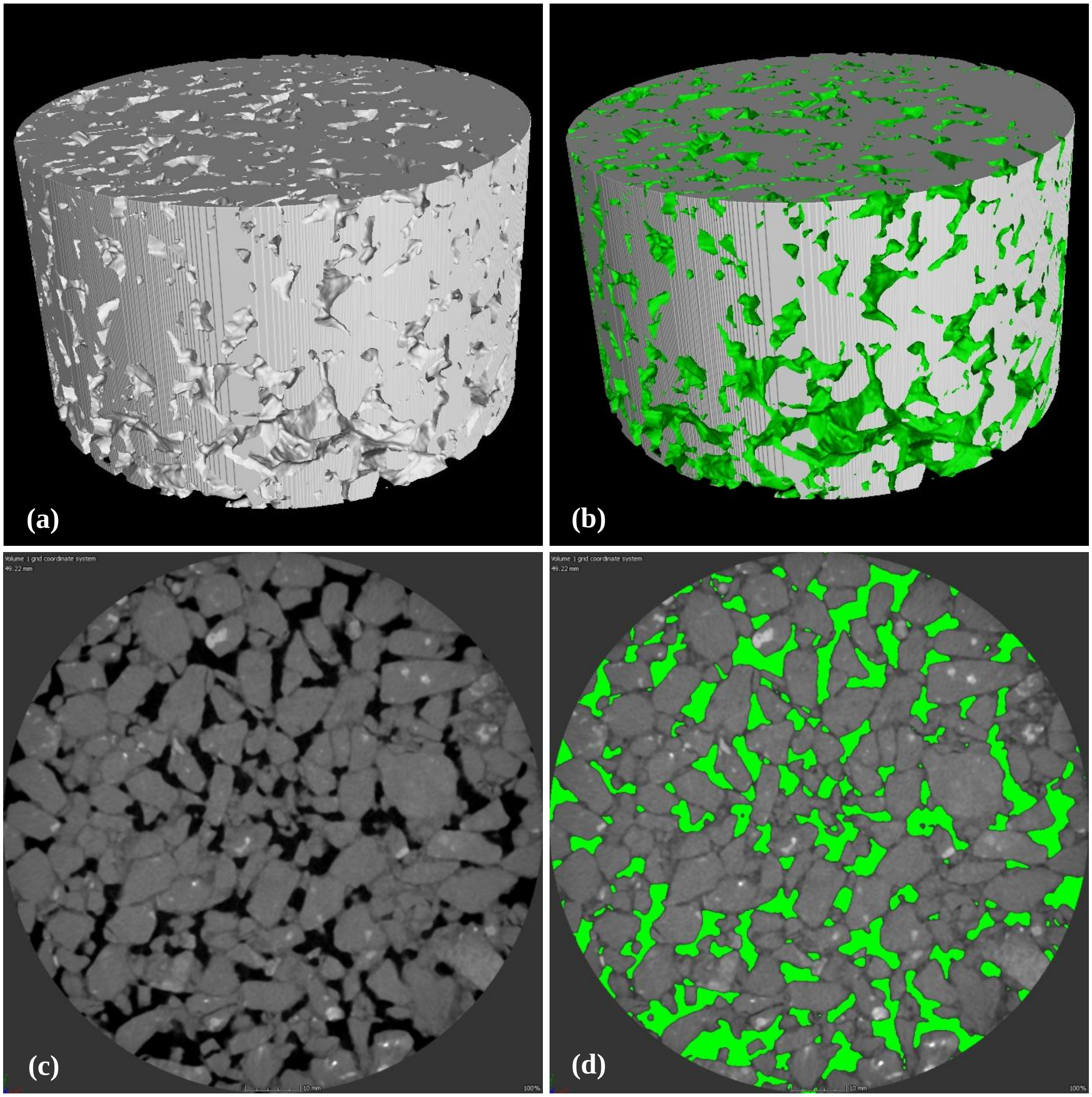

Fig. 4. Examples of the 3D visualization and 2D diametrical cross-sectional CT images of PMFC specimen: (a) and (c) before segmentation; (b) and (d) after segmentation.

Figure 5 shows the examples of 3D visualization and 2D diametrical cross-sectional CT scanning images of PMSMA specimen. From comparison of the images before and after the segmentation, it was found that the air voids were distinguished accurately by using the determined threshold values as well. The CT scanning images of PMSMA specimens were segmented successfully through using the ISO50 threshold method. The PMSMA specimens did not show a high percentage of inter-connected air voids as the PMFC specimens. However, the PMSMA specimens had certain percentages of air voids which were close to the surfaces and open. When the SSD method is going to be used for the PMSMA specimens, this should be taken into consideration for potential defect.

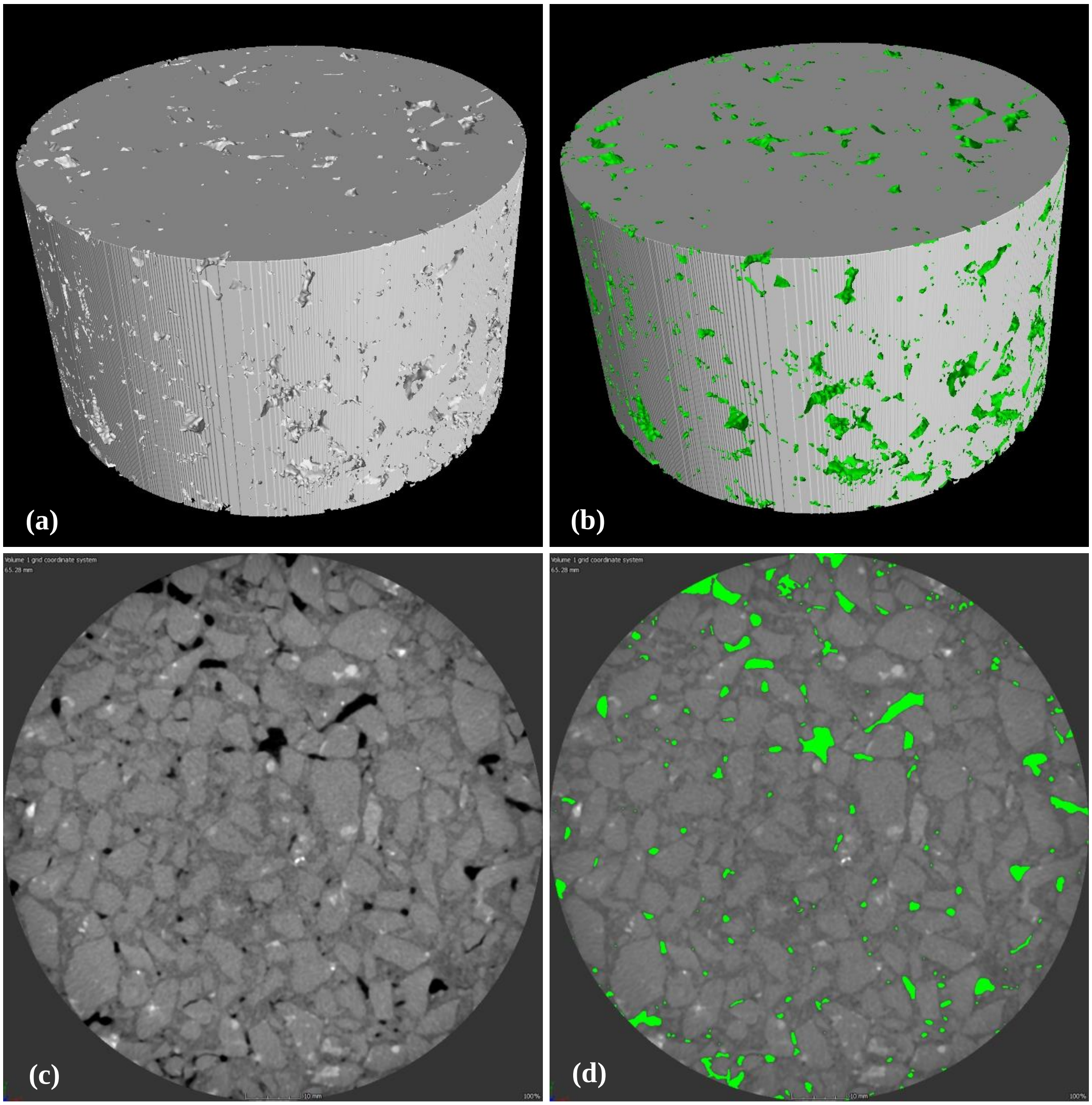

Fig. 5. Examples of the 3D visualization and 2D diametrical cross-sectional CT images of PMSMA specimen: (a) and (c) before segmentation; (b) and (d) after segmentation.

Afterwards, the “volume analyze” function within the VGStudio Max program was used to calculate the amount and volume of voxels in the region of interest. Since the resolution was 0.109×0.109×0.109 mm, it could be calculated that the volume of a single voxel was 0.00130 mm^3. The volume of total voxels for each scanned specimen was calculated by means of multiplying the amount of its total voxels by the volume of a single voxel, and the volume of air void voxels for each scanned specimen was also calculated. Finally, the air void content could be determined using the following equation:

$$Air\ void\ content = \frac{Volume\ of\ air\ void\ voxels}{Volume\ of\ total\ voxels} \times 100\% \tag{2}$$

Table 2

Results from the CT scanning image processing.

Sample	Threshold value	Volume of total voxels [mm^3]	Volume of air void voxels [mm^3]	Air void content [%]	Mean value of air void content [%]	St. D of air void content [%]
PMFC1	5181	447618	75662	16.90	17.66	0.60
PMFC2	4653	444450	81482	18.33		
PMFC5	5161	449159	81465	18.14		
PMFC6	5513	442866	78344	17.69		
PMFC7	5634	444437	76568	17.23		
PMSMA2	5902	452654	18369	4.06	4.32	0.37
PMSMA3	6139	450791	20784	4.61		
PMSMA4	6120	441237	19115	4.33		
PMSMA5	4365	441291	20940	4.75		
PMSMA6	7435	444417	17176	3.86		

Table 2 presents the results from the CT scanning image processing, including the threshold values, volume of the total voxels, volume of the air void voxels, and air void contents. The CT scanning tests were only performed on five specimens that were randomly selected for each type of mixtures. It was found that the air void content of PMFC specimens showed a mean value of 17.66% with a standard deviation of 0.60%. They were lower than the specified air void content (20%) for PMFC mixture according to the Hong Kong specification. But it should be noted that the specified air void content is measured using the dimensional analysis method. The air void contents of PMSMA specimens have a mean value of 4.32% with a standard deviation of 0.37%.

4.2. Statistical analysis for open-graded mixture

The bulk densities of all PMFC specimens were measured using the selected methods. Combining with the theoretical maximum density of PMFC mixture, the air void contents of these PMFC specimens were calculated. Table 3 presents the results of air void contents of the PMFC specimens from the bulk density measurements, as well as their water absorptions. It is logical that the open-graded mixture specimens had a relative high level of water absorptions. The air void contents obtained from the SSD method have the lowest mean value (11.19%), while those from the dimensional analysis method have the highest mean value (20.67%). Both of them are obviously different from the CT scanning results of PMFC specimens (17.66%). However, the results obtained from the automatic vacuum sealing and Parafilm coating, 17.80% and 18.26%, respectively, are reasonably close to the CT scanning results.

Table 3

Results of the air void contents and water absorptions of PMFC specimens from the bulk density measurements.

Sample	Air void content [%]				Water absorption [%]
	Dimensional analysis	Automatic vacuum sealing	Parafilm coating	SSD	
PMFC1	19.88	17.15	17.61	11.20	4.56
PMFC2	20.90	18.11	18.72	10.72	4.65
PMFC3	21.31	18.40	18.82	11.56	5.27
PMFC4	20.59	17.65	18.17	10.87	5.03
PMFC5	21.22	18.19	18.52	11.07	5.31
PMFC6	20.54	17.57	18.15	11.51	4.91
PMFC7	20.27	17.53	17.82	11.40	5.25
Mean	20.67	17.80	18.26	11.19	5.00
St. D	0.51	0.44	0.45	0.32	0.31

To further determine the statistical difference between the CT scanning results and the results from the bulk density measurements, the t-Test analysis was conducted in this research. The null hypothesis for this analysis is that there is no difference between the mean values of air void content of the PMFC specimens from the CT scanning and bulk density measurement methods. A significance level of 5%, or a confidence of 95%, was selected in the analysis. When the p-value is less than the level of significance, the null hypothesis is rejected. Table 4 presents the statistical analysis results for the air void contents of the PMFC specimens. It is known that the t-Test requires the underlying population from which the data samples are drawn is normally distributed. However, since the distribution of the test results from the SSD method did not meet this requirement, the t-Test was not conducted on the results from the SSD method.

Table 4

Statistical analysis results for the air void contents of PMFC specimens.

t-Test	CT scanning	Dimensional analysis	Automatic vacuum sealing	Parafilm coating
Mean value	17.658	20.562	17.710	18.164
Variance	0.36067	0.275	0.189	0.215
Observations	5	5	5	5
Pearson correlation		0.942	0.955	0.998
Degree of freedom		4	4	4
t-statistic		31.524	0.515	7.995
p-value (one-tail)		3.02E-06	0.317	6.64E-04
t-critical (one-tail)		2.132	2.132	2.132
p-value (two-tail)		6.03E-06	0.634	1.33E-03
t-critical (two-tail)		2.776	2.776	2.776

It is worth noting that from the t-Test analysis, both the one-tailed and two-tailed analysis results can be obtained, but the two-tailed test is more stringent, because the area in the outer tails outside the region of required certainty degree is split into two tails, and the calculated t-statistic values must be all the way out in the outer 2.5% of either tail for the t-Test to conclude with 95% certainty. In this study, the two-tailed p-values and t-critical values were analyzed. As shown in Table 4, the two-tailed p-value for the automatic vacuum sealing method is 0.634, which is larger than 5%. So the null hypothesis is accepted, indicating that there is no difference between the mean values of air void contents of the PMFC specimens from the CT scanning and the automatic vacuum sealing method. Thus, the measured bulk densities of the PMFC specimens using the automatic vacuum sealing method are reliable.

The two-tailed p-value for the Parafilm coating method is 1.33E-03, which is smaller than 5%. So the null hypothesis is rejected, indicating that there is a significant difference between the mean values of air void contents from the CT scanning and the Parafilm coating method. Besides, its t-statistic value (7.995) is larger than the two-tailed t-critical value (2.776). Therefore, it can be stated with 95% certainty that the mean value of the air void contents from the Parafilm coating method is higher than the CT scanning result. In other words, the measured bulk densities of the PMFC specimens using the Parafilm coating method are underestimated. The reason is that in the Parafilm coating method the bulk volumes of PMFC specimens were overestimated due to unavoidable wrapping of parts of air voids on rough surfaces of PMFC specimens. It was noted that this could be avoided by means of using automatic vacuum sealing method. The constant vacuum condition can makes sure a completely wrapping along the surface texture of PMFC specimens.

From Table 4, it can also be observed that the mean value of the air void contents from the dimensional analysis method is significantly higher than the CT scanning result, i.e., the measured bulk densities of the PMFC specimens using the dimensional analysis method are underestimated. The bulk volumes of PMFC specimens were calculated from the measured dimensions which included all air voids on surfaces of the specimens. The rough surfaces of PMFC specimens caused significant influence for measurement of bulk volume using this method.

4.3. Statistical analysis for gap-graded mixture

Table 5 presents the results of air void contents of the PMSMA specimens from the bulk density measurements, as well as their water absorptions. The water absorptions of these PMSMA specimens have a mean value of 0.30% and a standard deviation of 0.04%. The mean value is much less than the maximum 2% water absorption that is specified in the standard test method for bulk density using the SSD method. The mean values of air void contents obtained from the dimensional analysis, automatic vacuum sealing, Parafilm coating, and SSD methods are 5.64%, 4.27%, 4.41%, and 2.79, respectively. The difference between the highest and lowest mean values of air void contents is 2.85%, which is much less than that of PMFC specimens.

The air void contents detected by the CT scanning have a mean value of 4.322% and a standard deviation of 0.370%. The CT scanning results were also statistically compared with the results from bulk density measurement methods using the t-Test analysis with the null hypothesis that there is no difference in the mean values of air void content of the PMSMA specimens between the CT scanning and bulk density measurement methods. Table 6 shows their statistical analysis results.

Table 5

Results of the air void contents and water absorptions of PMSMA specimens from the bulk density measurements.

Sample	Air void content [%]				Water absorption [%]
	Dimensional analysis	Automatic vacuum sealing	Parafilm coating	SSD	
PMSMA1	5.32	3.82	4.02	2.30	0.30
PMSMA2	5.53	4.16	4.19	2.64	0.26
PMSMA3	6.01	4.78	4.81	3.12	0.32
PMSMA4	5.05	4.19	4.16	2.73	0.22
PMSMA5	6.42	4.75	5.04	3.22	0.34
PMSMA6	5.40	3.89	4.20	2.75	0.30
PMSMA7	5.78	4.28	4.45	2.80	0.34
Mean	5.64	4.27	4.41	2.79	0.30
St. D	0.46	0.38	0.38	0.31	0.04

Table 6

Statistical analysis results for the air void contents of PMSMA specimens.

t-Test	CT scanning	Dimensional analysis	Automatic vacuum sealing	Parafilm coating	SSD
Mean value	4.322	5.682	4.354	4.480	2.892
Variance	0.137	0.289	0.155	0.172	0.067
Observations	5	5	5	5	5
Pearson correlation		0.723	0.955	0.876	0.875
Degree of freedom		4	4	4	4
t-statistic		8.188	0.614	1.763	-16.795
p-value (one-tail)		6.06E-04	0.286	0.076	3.68E-05
t-critical (one-tail)		2.132	2.132	2.132	2.132
p-value (two-tail)		1.21E-03	0.572	0.153	7.37E-05
t-critical (two-tail)		2.776	2.776	2.776	2.776

For the automatic vacuum sealing and Parafilm coating methods, the statistical analysis results show that their two-tailed p-values are both larger than the significance level of 5%. So the null hypotheses of the statistical analyses for these two methods are both accepted. The air void contents obtained from the automatic vacuum sealing and Parafilm coating methods are not significantly different from the CT scanning results. This indicates that the measured bulk densities of PMSMA specimens using both the automatic vacuum sealing and Parafilm coating methods are reliable.

However, the two-tailed p-values for the dimensional analysis and saturated surface dry methods are both smaller than the level of significance, implying that the air voids obtained from those two methods are significantly different from the CT scanning results. The air void contents obtained from the dimensional analysis method are larger than the CT scanning results, indicating that the measured bulk densities of PMSMA specimens using the dimensional analysis method are underestimated, while the air void contents obtained from the SSD method are less than the CT scanning results, indicating that the measured bulk densities of PMSMA specimens using the SSD method are overestimated. The underestimating of bulk densities of PMSMA specimens in dimensional analysis was due to that the calculated bulk volume contained the air voids on surfaces of the specimens. The overestimating of bulk densities of PMSMA specimens in the SSD measurements was caused by drainage of water from the open air voids which were close to surfaces of PMSMA specimens.

5. Conclusions

In this study, X-ray CT scanning was used to detect the air voids of open-graded and gap-graded asphalt mixture specimens. The resultant resolution in CT scanning images of these specimens was 0.109 mm at all axial directions. From the CT scanning images with such resolution, bimodal histograms of gray values showing distinct peaks for the air voids and asphalt materials were acquired. The ISO50 threshold method was then successfully applied for segmenting the air voids and asphalt materials in the CT scanning images, which guaranteed the accuracy of air void contents measured from the CT scanning. Afterwards, the bulk densities of these open-graded and gap-gaped mixture specimens were measured using the dimensional analysis, automatic vacuum sealing, Parafilm coating and SSD methods, from which their air void contents were calculated and statistically compared to the CT scanning results. Based on the analyses, the following major conclusions can be drawn:

(1) For the open-graded asphalt mixture, the air void contents determined by the automatic vacuum sealing method were not significantly different from the CT scanning results, indicating that the bulk densities measured using the automatic vacuum sealing method are reliable, while

both the dimensional analysis and Parafilm coating methods underestimated the bulk densities of the open-graded asphalt mixture.

(2) For the gap-graded asphalt mixture, the air void contents from both the automatic vacuum sealing method and the Parafilm coating method are statistically same as the CT scanning results. Thus, the bulk densities measured using these two methods are reliable. The bulk densities measured using the dimensional analysis method are underestimated, while those measured using the SSD method are overestimated even though the water absorptions are only around 0.3%.

Conflict of interest

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors declare that they have no conflict of interest.

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