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Microstructure characterization of cold in-place recycled asphalt mixtures by X-ray computed tomography

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HIGHLIGHTS

- The concepts of air void gradation and thickness spectrum were developed.
- The uniformities of CIR mixtures were quantified.
- The impacts of compaction methods and aggregate gradations were statistically studied.

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ABSTRACT

This study investigated the microstructure features of cold in-place recycled (CIR) asphalt mixtures by the X-ray computed tomography (CT) and digital image processing (DIP) methods. A variety of CIR asphalt mixtures were prepared considering four types of aggregate gradation and three type of compaction method. The air void distribution characteristics of CIR specimens were analyzed based on the concept of air void gradation. A two-parameter Weibull function was used to fit the air void gradation, of which the statistical parameters are sensitive to both the aggregate gradation and compaction method. The concept of thickness spectrum was then developed to characterize the thickness distribution of cement asphalt (CA) mortar. Lognormal function was observed of good fitness of thickness spectrum. Finally, the uniformity index (UI) was built to evaluate the homogeneity of CIR mixtures and found the UIs of CIR mixture decreases gradually with the gradation from fine to coarse, and among the three compaction methods, the Superpave gyratory compaction is the best in terms of homogeneity. The findings of this study provide a solid foundation in exploring the internal structure and guiding the mix design of CIR mixtures.

1. Introduction

Cold in-place recycling (CIR) is widely used as a cost-effective and environmental-friendly rehabilitation measure of asphalt pavement. CIR mixtures are observed with sound performance of retarding the development of reflective cracking in the field due to its longer cracking propagation path but are susceptible to moisture damage and of low strength compared to hot mix asphalt (HMA) [1–4]. The mechanical response and performance of CIR mixtures lie on not only the material properties but also mixture structures.

X-ray computed tomography (CT) was widely used as a non-destructive measure to characterize the internal structures of HMA or base course material [5]. Coupling with image process techniques, the orientation, segregation, contact condition, and air void distribution in the asphalt mixture can be analyzed [6]. Yue et al. [7] used CCD digital camera to obtain the section profiles of asphalt mixture and identified the coarse aggregate particle size greater than 2 mm through image processing. Their research creatively depicts the orientation, shape and spatial distributions of coarse aggregates quantitatively. Masad et al. [8] obtained the internal structure of asphalt mixture via CT scanning technology and examined the impacts of compaction cycle, compaction method and aggregate gradation. Air voids of the specimens at the upper and lower ends are remarkably higher than that in the middle prepared by Superpave Gyratory Compactor (SGC). Furthermore, Wang et al. [9] conducted a spatial voids structure analysis of semi-rigid base materials and quantified the influence of three variates on the spatial distributions of the

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internal structures. The results suggest that the mass loss ratio and strength loss ratio of the samples increase with the freeze–thaw cycle but decrease with the cement content and the curing time.

With the microstructure information, the three-dimension numerical models of asphalt mixture were reconstructed to carry out the performance and mechanical analysis [10]. Elseifi et al. [11] carried out the dynamic modulus test and flow number test of HMA with the addition of different contents of reclaimed asphalt pavement (RAP). The results show that the damage incurred in the dynamic modulus test is minimal and homogeneous while the damage incurred in the flow number test is significant and heterogeneous. Shaheen et al. [12] presented an image-based method for the quantification of air voids and fatigue damage employing CT. Both two-dimension and three-dimension image analysis procedures were developed for evaluating the fatigue damage of HMA.

The applications of CT in CIR asphalt mixture are less. Gao et al. [13] investigated the characteristics of air voids in CIR mixtures with CT and digital image processing (DIP) methods. The volume, size, and number of air voids in CIR specimens were statistically analyzed considering three types of aggregate gradations and three types of compaction methods. Zhao et al. [14] created a three-dimension heterogeneous fracture model to simulate complex cracking development in CIR mixture in which cohesive zone model (CZM) was utilized to estimate the crack resistance of the interface based on laboratory fracture test results.

In this study, the microstructure parameters of CIR mixtures were thoroughly investigated in terms of the three components of asphalt mixture by CT and digital image processing (DIP) methods, including air void, asphalt mortar and coarse aggregate. Based on the research of Gao et al. [13], this research investigated the air void distributions of four types of CIR mixtures, and further developed the concept of thickness spectrum to characterize the thickness distribution of cement asphalt (CA) mortar. And the uniformity of CIR mixtures under different compaction methods and aggregate gradations was also quantified by analyzing the distribution of coarse aggregate particles.

2. Mixture design

The recycled asphalt pavements (RAPs) from the field project were collected to prepare the specimens of CIR mixtures. The design procedure of the CIR mixture was performed in accordance with the CIR specification of Jiangsu Province, China [15]. Three basic types of CIR mixtures, CIR-13, CIR-20 and CIR-25, were prepared. Because the percentage of coarse aggregate was reduced due to the mill process, coarse basalt aggregates were added to the CIR-25 mixture to form CIR-25A. A cationic slow-setting (CSS) asphalt emulsion was selected as the recycling additive to be compatible with the RAP materials. The gradations and optimum asphalt emulsion contents are shown in Fig. 1.

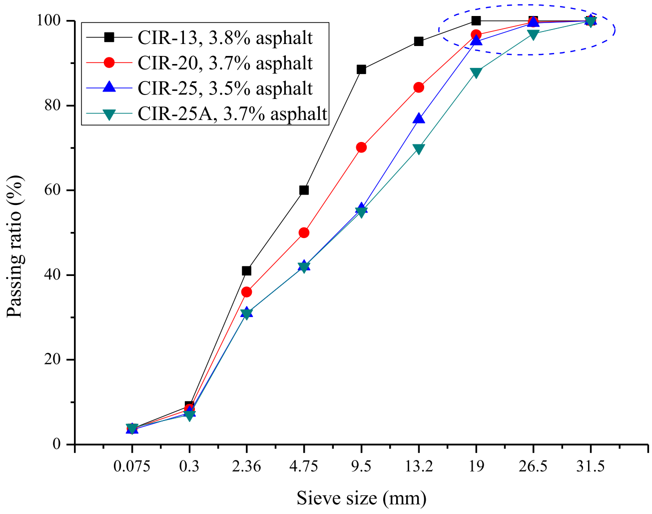

Fig. 1. Aggregate gradations of four types of CIR mixtures.

The gradations of CIR-13, CIR-20 and CIR-25 have great difference, but the passing ratio of CIR-25 and CIR-20 is very close when the sieve size is large. With the addition of coarse aggregates, the gradation of CIR-25A mixture becomes the typical coarse grained type. Three types of compaction methods, Superpave gyratory compactor (SGC), Marshall, and static load, were used to fabricate the CIR specimens.

3. CT scanning and image processing

The CT scanner Compact-225 of YXLON Company was used to obtain the internal structure of CIR mixture at a slice interval of 1 mm. Using CIR-25 mixture as an example, the CT slice is an 8-bit grayscale image which was first processed in MATLAB software to eliminate the noise. Uneven brightness was observed in the obtained image and caused the same material to have different grayscale values at different locations. The issue occurred possibly because of beam hardening or aging of CT scanner and was processed by the top-hat transformation. A contrast stretching treatment was further applied to improve the quality of images [16].

In the image segmentation process, the most important step is to determine the threshold of the grayscale T1 to determine air voids and asphalt mortar, and the threshold of the grayscale T2 to determine asphalt mortar and coarse aggregate. The Otsu's algorithm [17] was used as the segmentation method to confirm the optimum thresholds during the image segmentation procedure. Specifically, the pixel of the whole image was first taken as the object and the threshold T1 was calculated by the OTSU method. Then the pixel of the gray value between T1 + 1 ~ 255 was taken as the object, and the threshold T2 was calculated again by the OTSU method. The threshold T1 distinguishes the gap from the background and divides the asphalt and aggregate particles into a class; the threshold T2 can distinguish the aggregate particles and divide the gap, the background and the asphalt mortar into a class. Afterward, a series of image addition and subtraction can be used to obtain the respective images of air voids, asphalt mortar and aggregate particles.

The three binary images that represent air void, asphalt mortar and coarse aggregate were obtained, as shown in Fig. 2 (from a to d). The processed images were then imported into VGStudio MAX 2 for 3D reconstruction, as shown in Fig. 2e.

By comparing the volume parameters of the 3D reconstruction process with the measured volume parameters, the effect of the material classification can be evaluated and thus the rationality of threshold T1 and T2 in image segmentation process can also be verified. In this study, the air void and the volume of coarse aggregate were checked, as shown in Table 1.

The calculated air voids of all specimens are smaller than the measured ones, but the deviations are small, about −1.0%. The reason for the deviations is probably due to the fact that some air voids in the mixtures are not identified by the CT scanning test. The particle volumes of coarse aggregate are also less than the measured values, and the deviations are less than -5%. The image processing precisions in terms of the deviations of air void content and volume of coarse aggregate are acceptable.