Evaluation of Fiber Distribution in Steel Fiber Reinforced Asphalt Concrete based on CT Image Analysis

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ABSTRACT: The premise of steel fiber reinforced asphalt concrete (FRAC) to exhibit multifunctional applications is that fibers are uniformly dispersed in the asphalt mixtures. In this paper, image analysis method was applied to evaluate the fiber distribution in different asphalt mixture samples. X-ray computed tomography (CT) scanner was adopted to capture the images and image processing software (Image-Pro Plus) was assisted to accomplish the following analysis. The distribution coefficient was introduced to evaluate quantitatively distribution of the steel fibers (SFs), the higher value of distribution coefficient, and the more uniform distribution the SFs. Asphalt mixtures with 4% SFs showed better fiber distribution than that with 10% SFs. The distribution coefficient of samples with 10% SFs were 0.7427 and 0.7861, while distribution coefficient of samples with 4% SFs were all over 0.8, which indicates asphalt mixture incorporated with less amount of fiber can obtain more uniform distributed fibers.

INTRODUCTION

Asphalt concrete is the most widely used material as highway pavement due to its various advantages. However, asphalt pavement is vulnerable to environmental effects (like moisture damage, temperature gradient, oxidation etc.) and daily traffic loadings (Barra et al., 2012), which probably leads to cracking, raveling and fatigue damage.

Adding a small amount of fiber in asphalt mixture is recognized to be an effective method to improve pavement performance, which has gotten much attention due to their improving effects (Abtahi et al., 2010). Compared with ordinary asphalt concrete, fiber reinforced asphalt concrete (FRAC) exhibits several advanced properties, such as improving water stability, rutting resistance and anti-cracking performance in a cold atmosphere (Lee et al., 2005, Park, 2012). Conductive fibers and fillers transfer the insulated asphalt concrete to the electrical conductor, which enables the asphalt concrete to multifunctional applications, including snow melting, deicing, self-monitoring of pavement integrity, induction heating, and energy harvesting (Wu et al., 2005, Liu and Wu, 2011, García et al., 2013a, Menozzi et al., 2015).

Steel fiber has been considered to be the promising conductive addition to obtain reinforcement and electrical conductivity in asphalt mixture (Guo, 2014, García et al., 2009). However, the requirements for the mixture were that it should be free of clusters of fibers. Various studies indicated that the reinforcing abilities of fibers
Based on how the fibers were distributed in the asphalt mixture (García et al., 2012, García et al., 2013b). Poorly distributed fibers provided little or no reinforcement, on the contrary, they even acted as flaws in asphalt mixture. Therefore, fiber distribution should be controlled in fiber reinforced asphalt concrete design.

EVALUATION METHODS ON DISTRIBUTION OF FIBERS

Advanced techniques to characterize fiber distribution has already been successfully used in cement based composites, including X-ray transmission photograph method, AC-Impedance spectroscopy method, electrical resistivity measurement method and image analysis method (Yang, 2002, Cavalaro et al., 2014).

Electrical resistivity measurement (ERM) method was based on the relationship between fiber distribution and electrical conductivity of the specimen (Lataste et al., 2008). However, this method cannot tell the actual distribution of fibers. Factors, such as structure of asphalt concrete, air voids, diameter and length of fibers, may lead to great diversity of electrical resistivity.

Image analysis method was regarded to acquire a more intuitive sight of fiber distribution (Liu et al., 2012). Various image acquisition approaches, like CDD digital camera, fluorescence spectroscopy, scanning electron microscope (SEM) and X-ray CT scanning can be adopted. X-ray CT is a completely non-destructive technique for visualizing features or special additions in solid composites. Wang et al. (2014) adopted the X-ray CT scanner to capture the images, and mathematical calculation based on the areas of different components was conducted to compare the degree of fiber distribution.

EXPERIMENTAL METHODS

Raw materials
In this experiment, a Superpave asphalt mixture (Sup-13) with 12.5-mm nominal maximum aggregate size was adopted. The gradation of Sup-13 exhibited in Table 1. Both aggregates and fillers used were local limestone.

| Gradation | Sieve size, mm (% passing) |
|-----------|----------------------------|
|           | 16.0 | 12.5 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
| Sup-13    | 100  | 96.6 | 81.1 | 48.0 | 31.2 | 18.9 | 11.7 | 7.7  | 6.7  | 5.7   |

Asphalt binder used in this study was SHELL-70, which met the Superpave PG binder requirements for PG 64-22. Steel fibers utilized in specimens are low-carbon steel, with smooth surface, electrical resistivity of $7 \times 10^7 \Omega \cdot \text{cm}$, and density of about 7.5 g/cm$^3$. Based on former researches, steel fiber with diameter of 0.05mm (Type I) was adopted, and the fibers were cut into approximately 8 mm long.

The optimum asphalt content is 4.8% and air void is 5.0%. According to previous studies (García et al., 2009), to reach the percolation threshold, the mass fraction of
steel fibers was around 6.0%. In order to analyze the effect of fiber content in FRAC, steel fiber dosage of 4.0% and 10% by weight of the whole asphalt mixture were introduced.

**Test samples preparation**
Cylindrical specimens with 100 mm diameter and approximately 160 mm height were fabricated using a Superpave gyratory compactor, then the specimens were cut into 40-45 mm in diameter for CT scan procedure. Three candidate samples were prepared for each steel fiber dosage (4.0% and 10%), then the two well-saved samples after cutting and polishing were chosen as the X-ray CT scan samples (seen in Fig1).

![Test samples and Size of sample](image)

(a) Test samples  
(b) Size of sample  
*Figure 1. X-ray CT scan samples.*

**Image analysis method**

**Image acquisition**
A high-resolution Micro-focus Computed Tomography System (Y.CT Precision S) produced by YXLON was employed to acquire the microstructural information from FRAC. The high voltage range, tube current and max tube power were 10-225kV, 0.01-3.0mA and 320W respectively. The operation procedure consists of the volume scan (cone bean geometry) and digital radiography, which were accomplished by two sides of the system (seen in Fig.2).

The discrimination of different components in CT images is based on the density of material. As the density of steel fibers is the largest, so the steel fibers have the maximum gray-scale, and show the brightest colors from the CT images.

![Signal reception side and X-ray emission side](image)

(a) Signal reception side  
(b) X-ray emission side  
*Figure 2. Signal reception side (left) and X-ray emission side (right).*
**Image Processing**

Image-Pro Plus (IPP) was utilized to process the images with following steps: (a) Image filtering: the $3 \times 3$ mode median filter was adopted to remove impulsive noise and replaces center pixel with median value in its neighborhood. (b) Image sharpening: $7 \times 7$ mode in the sharpen filter was used to enhance the detail representation of fuzzy parts. (c) Image contrast enhancement: image contrast enhancement was conducted to improve the perceptibility of fibers and brightness difference between fibers and the surrounding asphalt mixture.

![Original image](image1.jpg) ![Enhanced image](image2.jpg)

**Figure 3. CT image of specimen slices.**

Afterwards, IPP was utilized to conduct the image segmentation. The target of image segmentation is to determine the area of interest (AOI) and then transfer AOIs into objects that can be analyzed.

Fig 4 illustrates the three types of AOIs picked up from the image, which were segmented through the limited intensity value (from 170 to 255). (1) AOI1 that inside the aggregates was non-steel fiber images, which showed the similar grayscale with steel fibers but different size and shape from steel fibers. They must be removed from the image. (2) AOI2 was the vertical fibers distributed in the asphalt concrete slices, while its value played marginal impact to the calculation. (3) AOI3 was the horizontal fibers distributed in the asphalt concrete slices, and an obvious fiber shape could be seen in the image. Moreover, specific aspect ratio conducted to assure all of the steel fibers images were selected.
RESULTS AND DISCUSSION

Currently, distribution coefficient was mostly defined by the number of objects in each image and the total number of them (Zhang et al., 2014). In this study, image number ended with 0 and 5 were selected to do the statistics. The total unit area of target objects in each image was calculated, and distribution coefficient \((D_{sf})\) of steel fiber was defined as following:

\[
A_{ave} = \frac{\sum_{i} A_i}{n}
\]

\[
D_{sf} = \exp\left(-\frac{\sum_{i} A_i}{A_{ave}} 1 \right)^2 / n
\]

Where \(A_i\)-the total area of target objects at image \(i\), \(n\)-the total numbers of the selected images.

Fig. 5 exhibits the unit area value at each image from different specimens, and the average value for 10sf-1, 10sf-2, 04sf-1 and 04sf-2 were 2804.81, 2056.37, 1723.11 and 1472.34 respectively. Specimen 10sf-1 and 10sf-2 were both drilled from one cylindrical asphalt mixture specimen, while the deviation between different images in 10sf-1 was larger than 10sf-2. The gap between the maximum and minimum unit area in 10sf-1 was the highest among all the specimens. However, values were more centralized in specimen 04sf-1 and 04sf-2.
Figure 5. Total unit area in each image and average value.

Figure 6. Distribution coefficient.

Distribution coefficient calculated through equation (2) was explained in Fig 6, which proved the obvious deviation of fiber distribution in asphalt mixture with 10% steel fibers again. Distribution coefficients of 04sf-1 and 04sf-2 (0.8068, 0.8096 respectively) were higher than samples with 10% steel fibers, which indicates asphalt mixture incorporated with less amount of fiber could obtain more uniform distributed fibers.

CONCLUSION & FURTHER RESEARCH

A novel distribution coefficient of steel fibers was proposed to evaluate the fiber distribution in FRAC. The higher value of distribution coefficient, and the more uniform distribution the SFs. The distribution coefficient of samples with 4% SFs were all over 0.8, which were higher than the samples 10sf-1 and 10sf-2, with the distribution coefficient were 0.7427 and 0.7861 respectively. It indicates that asphalt mixture incorporated with less amount of fiber can obtain more uniform distributed fibers.

This is a preliminary research about the evaluation on the degree of fiber distribution in steel fiber reinforced asphalt concrete (SFRAC). Based on the CT slices, most fiber images were found in vertical direction, which demands to apply
other measures to analyze the impact of horizontal distributed fibers and also the orientation factor when mixing the fibers with asphalt mixture. Moreover, three-dimensional reconstruction is expected to conduct both vertical and horizontal fiber distribution analysis as well as the orientation condition of steel fibers in asphalt concrete.

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