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Study on 3D spatial distribution of steel fibers in fiber reinforced cementitious composites through micro-CT technique

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HIGHLIGHTS

- The fiber distribution in cementitious composites is characterized quantitatively by a nondestructive testing method.
- Fiber orientation distribution (FOD) and fiber spacing distribution (FSD) can be obtained.
- Comparison of fiber distribution from micro-CT technique and 2D image analysis are given.

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ABSTRACT

Fiber distribution in fiber reinforced cementitious composites (FRCC) is a critical factor affecting the reinforcement of fiber to composites. However, evaluation of fiber distribution in 3-dimension (3D) space has always been a great challenge due to the lack of transparency of FRCC and random distribution of fiber. To address this problem, micro-computed tomography (micro-CT) was used to characterize fiber distribution in this study, which permitted 3D visualization within the materials. By 3D image reconstruction, processing and analysis of CT images, the curves of fiber orientation distribution (FOD) and fiber spacing distribution (FSD) in cementitious composites can be obtained, and the orientation factor and dispersion coefficient of fiber can also be determined. The effect of aggregate size and content on fiber orientation distribution in cementitious composites is more obvious than that on fiber spacing distribution. Compared to conventional approach of 2D image analysis of cross-section of FRCC, the micro-CT image technique appears more intuitive and accurate, especially in the assessment of fiber dispersion.

1. Introduction

Fiber reinforcement is commonly used to improve the strength and toughness of cementitious composites. Contrary to normal concrete, once the matrix cracks, a marked characteristic of fiber reinforced cementitious composites (FRCC) is fiber becoming the main bearer of external force and inhibiting the expansion and extension of cracks. The efficiency of fibers depends on the fiber properties (elastic modulus, strength, stiffness and so on) and fiber distribution. It was shown that, cementitious composites have better mechanical properties when fibers are evenly dispersed and parallel orientated to the load direction [1,2].

In general, fibers are considered to be distributed randomly in all directions. However, the real fiber distribution is strongly influenced by various factors, such as fiber characteristics (fiber diameter, length, shape, content and so on), matrix feature (matrix composition, rheological behavior, and so on), and placing methods [3–5]. Aggregate is an important part of FRCC, and its size and content will influence the uniformly of fiber distribution. But there are few reports on the effect of aggregate on fiber real distribution, due to the difficulty of characterization of fiber distribution.

In developing FRCC for structural applications, characterizing and controlling fiber distribution is critical to maximize the mechanical properties. The quantification of fiber distribution can also lead to the development of constitutive models of FRCC based on single fiber pullout contributions. Therefore, several studies have previously been undertaken to characterize fiber distribution. Image analysis of cross-section of FRCC is the most widely used, through X-ray photographs [6,7], microscope [8,9], scanning electron microscope [10,11] and so on. But it is destructive and time consuming. Electrical measurement technique is a non-destructive method to characterize fiber distribution [12–14], but it cannot give real fiber distribution, and can only be applied to electricity conductive fibers, such as steel fibers and carbon fibers.

As a novel and non-destructive method, CT technique was first applied in medical research. But with the expansion of its application fields, it has been increasingly used in the research of cementitious composites. The advantage of CT technique is

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non-destructive, efficient, and accuracy. By combining with 3D image reconstructive technique, the size and distribution of fiber in 3D space can be clearly observed and measured, which can make up for the lack of 2D image analysis and resistivity testing for fiber distribution measurement. Farhat et al. [15] gave the X-ray absorption density contours and the corresponding fiber count contours by CT imaging. Barnett et al. [16] combined the CT technique and conductivity to prove the accuracy of fiber distribution test, and showed good agreement. Krause et al. [17] proposed a mathematical technique based on the structure tensor to determine the local orientation of fibers. So far, many research about the CT technique used for characterization of fiber distribution, was focused on the processing and analysis of 2-D images of cross-sections, and do not analysis the material from the view of 3-D solids. The unique advantage of CT technique has not been fully exploited.

Therefore, this paper aims at establishing the characterization method of fiber distribution in 3D space by micro-CT imaging, and presenting the effect of aggregate on fiber orientation distribution (FOD) and fiber spacing distribution (FSD). The results from micro-CT imaging and 2D image analysis of cross-section will also be compared. The quantification of fiber distribution in 3D space can be used to the analysis and prediction of mechanical performance of FRCC.

2. Experiments

2.1. Raw materials and mix proportions

An ordinary Portland cement (P.||52.5), silica fume and fly ash were used as the binder phase of cementitious composites. The sand fineness modulus was 2.5. In order to improve the fluidity of cementitious composites at low water–binder ratio, a polycarboxylate superplasticizer (PCA IV-B) was used with a solid content of 30%, provided by Jiangsu Bote New Materials Co., Ltd. The steel fibers were round and straight with length of 13 mm, diameter of 0.2 mm and tensile strength of greater than 2800 MPa. Three ranges of coarse aggregate size were used, including 5–10 mm, 10–15 mm, and 15–20 mm; three ratios of binder to aggregate were selected, including 1:1.5, 1:2.0 and 1:2.5. The mix proportions of FRCC were shown in Table 1. In order to get similar fluidity, the PCA content changed with different mix proportions (see Tables 2 and 3).

2.2. Sample preparation

To ensure the characterization accuracy of fiber distribution in FRCC, the measures should not be influenced by the wall effects along the sides of the mold. Fibers are oriented differently near the walls of the specimens. For this study, a 100 mm × 100 mm × 400 mm (dimensions of tensile test) cuboid of FRCC was cast and the central parts of the sample (50 mm × 50 mm × 50 mm) was cut for the test of fiber distribution, as shown in Fig. 1.

3. Characterization of fiber distribution

3.1. Image acquisition

A high-resolution Micro-focus Computed Tomography System (Y.CT Precision S) produced by YXLON was employed to acquire microstructural information from FRCC. The voltage and current of X-ray tube were 195 kV and 0.45 mA, respectively. The number of detector elements was 1024, and the reconstructed 3D images were composed of 1024 × 1024 × 1024 pixels in *X*, *Y* and *Z* axis, respectively. The resolution of each voxel was 0.07 mm × 0.07 mm × 0.07 mm.

The identification of different materials from CT images is based on the density of material. The bigger the density of material is, the higher the gray-scale of CT images of material will be. Among the constituent materials of FRCC, the density of steel fibers is the largest, so the steel fibers have the maximum gray-scale, and show the brightest colors from CT images of FRCC (seen in Fig. 2(a)). Therefore, the extraction of steel fiber images is fairly easy to implement.

Table 2
Parameters applied for fitting theoretical expressions in Fig. 4(a).

Binder to aggregate ratio	*a*	*b*	R^2
1:1.5	3.296	2.893	0.933
1:2.0	3.104	2.728	0.942
1:2.5	3.077	2.343	0.863

Table 3
Parameters applied for fitting theoretical expressions in Fig. 4(b).

Coarse aggregate size	*a*	*b*	R^2
5–10 mm	3.104	2.728	0.942
5–15 mm	3.080	2.430	0.893
5–20 mm	2.931	2.111	0.921

3.2. Image processing

3.2.1. 2D image enhancement

Image enhancement is the improvement of digital image quality, without the degradation of image information. In order to improve the accuracy of fiber identification and analysis, contrast enhancement was used to improve the perceptibility of fibers in the image through enhancing the brightness difference between fibers and the around cement pastes.

3.2.2. 2D image segmentation

Image segmentation is a crucial step transiting from image process to image reconstruction and analysis, which is the process of detecting objects or the region of interest (ROI) from input image. In many image segmentation methods, thresholding is a simple and efficient technique for image segmentation in digital image processing [18,19], and the fiber-only images can be obtained by filtering out image elements with grey scale levels lower than a predetermined threshold value (seen in Fig. 2(b)). After image thresholding segmentation, many 'noises' may be exist in the binary image, which showed similar gray scale with steel fiber in the original image, and it should be removed. Operations of mathematical morphology and area feature identification were used to obtain the fiber-only image (seen in Fig. 2(c)).

Table 1
Mix proportions of FRCC (kg/m^3).

No.	W/B	B/A	Cement	Silica fume	Fly ash	Sand	Coarse aggregate			Water	PCA	Fiber
							5–10 mm	10–15 mm	15–20 mm			
L1	0.20	1:2.0	608	38	114	608	912	0	0	152	7.2	40
L2	0.20	1:2.0	608	38	114	608	456	456	0	152	8.0	40
L3	0.20	1:2.0	608	38	114	608	365	365	182	152	8.4	40
L4	0.20	1:1.5	720	45	135	540	810	0	0	180	7.6	40
L5	0.20	1:2.5	528	33	99	660	990	0	0	132	9.0	40