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Characterization of carbon fiber distribution in cement-based composites by Computed Tomography

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HIGHLIGHTS

- Sub-mm pores, highly clustered, clustered and fiber sparse areas were found in CFRC.
- Planar distribution (P_d) and spatial distribution (S_d) deteriorate with growing CF usage.
- P_d, S_d and volume factor highly influences the flexural strength of CFRC.
- P_d and volume factor greatly impacts the compressive strength and resistivity of CFRC.

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ABSTRACT

Carbon-fiber-reinforced cement-based composites (CFRC) have been considered as an innovatively functional civil engineering material for self-monitoring buildings, snow-melting pavement and smart pavement. However, the distribution of carbon fiber can significantly influence the performance of CFRC, especially their mechanical and electrical properties. The main purpose of this research is to explore the effect of carbon fiber distribution on mechanical and electrical properties of CFRC. For this purpose, the components in consecutive slices of Computed Tomography (CT) images were identified and segmented by using their grayscale thresholds. The typical morphology of each component in micrograph of fracture surface was classified. The classification was used to verify the results identified by their grayscale in CT images. Indexes of planar distribution (P_d), spatial distribution (S_d) and volume factor were designed and calculated using 3D reconstruction model of the specimen. The resistivity, bending strength, bending fracture energy and compressive strength of specimens with different carbon fiber contents were tested. Finally, the grey entropy correlation analysis (GECA) was conducted to determine the effect of fiber distribution on the performances of CFRC. Results showed that four components contained in CFRC are the sub-mm pores, highly clustered area, clustered area and fiber sparse area. The volume fractions of pores (V_P), highly clustered area (V_H), and clustered area (V_C) increase with the increase of carbon fiber content while the sparse area (V_S) shows the opposite trend. The P_d and S_d increase with the increase of carbon fiber content. S_d has greater influence on the bending strength and toughness of CFRC. Volume factor plays a more important role on compressive strength and electrical resistivity of CFRC.

1. Introduction

Carbon fiber is considered to be one of the most promising engineering materials with excellent mechanical and electrical properties [1,2]. The incorporation of carbon fibers enables the conventional cement-based materials to possess excellent mechanical and electrical properties [3–7]. To date, the carbon-fiber-reinforced cement-based composites (CFRC) have been considered as an innovatively functional civil engineering material for self-monitoring buildings, snow-melting pavement and smart pavement [8–13]. However, the accuracy and the effectiveness of the functions that CFRC provide often depend on the distribution of carbon fibers in the cement-based composites. Consequently, the desirable distribution of carbon fiber in cement-based composites

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is the foundation to the functional properties of CFRC [14]. The distribution of carbon fibers is a wide concept, which includes not only the aggregation degree of carbon fibers in the composites but also the spatial uniformity of the aggregation degree. Therefore, the carbon fiber distribution essentially refers to the homogeneity of the CFRC. Obviously, a reliable quantitative evaluation method for the carbon fiber distribution in CFRC is necessary.

On the basis of previous studies [15–20], the evaluation methods can be classified into macroscopic test method and microscopic observation method. For macroscopic test, a Chinese technical specification entitled *Technical Specification for Fiber Reinforced Concrete Structures in China (CECS38:2004)* [15] and an American test standard named *Standard Test Method for Determination of Glass Fiber Content in Glass Fiber Reinforced Concrete (ASTM C1229-94)* [16] are recommended as traditional and popular method (wash-out method) to measure the fiber dispersion in fresh cement concrete mixtures, respectively. The mechanism concerning this method is to wash out the cement from the fresh fiber reinforced cement paste and weigh the fibers left on the sieve. The fiber dispersion can be represented by the mass deviation of multiple samples. In addition, Yang, et al. [17] and Woo, et al. [18] reported that the fiber dispersion in the conductive cement concretes, such as CFRC and steel fiber reinforced concrete, can be characterized by the deviation in the electrical resistivities of multiple specimens. In microscopic observation, Kim et al. [19,20] used a CCD camera to capture the fluorescence image of the PVA fibers in cement-based composites; and the fiber distribution coefficient can be evaluated by measuring the features of the fluorescence images. However, the limitations of these methods remain. For example, the result that wash-out method acquired is significantly influenced by flow intensity and flushing time. Meantime, the results that the conductivity method obtained evidently vary with sample humidity and bonding condition between the electrode and sample. At last, the observation area of scanning electron microscope or optical microscope is limited; therefore, this method may be more suitable for the detection of typical distribution characteristics. Most importantly, the most challenging task is to use these methods to describe the aggregation of carbon fibers and the spatial distribution of the aggregation. On the other hand, previous studies [21–24] have demonstrated that the X-ray CT technology is a novel method for evaluating the internal properties of cement-based composites. For example, Vicente, et al. [21] studied the position and orientation of steel fibers in cement-based composites via CT scan. Meanwhile, Balázs et al. [23] discussed the effect of mixing parameters on the post-cracking residual flexural and compressive strengths of steel fiber reinforced concrete by using CT scan. At last, Bordelon et al. [24] developed a method to determine the individual fiber spatial distribution inside the concrete.

It is widely accepted that the fiber content plays a vital role in the mechanical and electrical properties of CFRC. However, previous studies have shown extensively that the fiber content and CFRC performances (e.g. bending strength) are not linear correlated [25,26]. For example, literature [27] reported that the flexural strength of CFRC was not significantly improved when the carbon fiber content was below a certain level (increases equidistantly). Noticeably, this effect indicates that the carbon fiber added may not be helpful if the carbon fiber is insufficient and is poorly dispersed. Accordingly, following questions arose on this issue.

- What is the effect of carbon fiber contents on the distribution morphology of carbon fiber in CFRC?
- How to quantitatively characterize the distribution of carbon fiber in CFRC?
- What is the effect of carbon fiber distribution on the mechanical and electrical properties of CFRC?

In this work, the above three questions are discussed as the primary purpose of this research. Specifically, the components in consecutive slices of CT images were identified and segmented by using their measured grayscale threshold. The typical morphology of each component in micrograph of fracture surface was classified, and the results were adopted to verify the results identified by their grayscale in CT images. The indexes of planar distribution, spatial distribution and volume factor were designed and calculated by the 3D reconstruction model of the specimen. The resistivity, bending strength, bending fracture energy and compressive strength of specimens with different carbon fiber contents were tested. Finally, the correlation between distribution index and performances of specimens was analyzed via grey entropy analysis theory. For convenience, the outline of this work is summarized and illustrated in Fig. 1.

2. Experiments

2.1. Raw materials

In CFRC specimens, the aggregates are not introduced since the identification of the fiber distribution is a difficult work with the presence of aggregates in CFRC. Therefore, only three raw materials involved, they are ordinary Portland cement, short-cut polyacrylonitrile (PAN)-based carbon fibers and mixing water. The technical properties of cement and carbon fiber are shown in Table 1 and Table 2, respectively. The used cement is qualified with Chinese technical specification of *Standards of Common Portland Cement in China* (GB 175-2007) [28].

2.2. Sample preparation and tests

2.2.1. Preparation of CFRC specimens

Four carbon fiber contents were designed as 0%, 0.4%, 0.8% and 1.2% of cement mass, respectively. The mixing water-cement ratio remained 0.33 for each specimen. The specimens are prepared through the after-mixing method, which means that the carbon fibers were added after the preparation of cement mortar. This method is reported as a better way to enhance the fiber distribution compared with before-mixing [17]. The procedures are: 1) the mixing water and cement first mixed via a cement mortar mixer, the stirring time was 30 s with the stirring speed of 60 r/m; 2) the carbon fibers are weighed and added into cement mortar and the stirring time usually should take more than 120 s; and 3) the 40 mm × 40 mm × 160 mm steel models are adopted to prepare the specimens. The curing conditions for CFRC specimens were temperature 20 ± 2 °C and relative humidity 93%. The curing age was 28 days.

The specimens were labeled as CF0, CF0.4, CF0.8 and CF1.2 (by its carbon fiber content). Four specimens were prepared for different carbon fiber content. Among four specimens, the first one was utilized to observe the microscopic distribution of carbon fibers at the fracture surface. Observation results can be used for the identification of X-ray CT images. The other three were used for CT scanning and the performance tests.

2.2.2. X-ray CT scanning

Before the Computed Tomography (CT) scanning, the specimens should be dried in the furnace for at least 6 h to remove internal free water thereby avoiding interference on CT image quality; and the furnace temperature was 45 °C. The technical properties of the X-ray CT system used can be found in Table 3.

The CT image quality mainly depends on two key parameters which are spatial resolution and contrast resolution. The spatial resolution of the CT system determines the smallest object size