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Preparation of carbon fiber reinforced cement-based composites using self-made carbon fiber mat

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HIGHLIGHTS

- Carbon fiber mat is made using cellulose as the dispersant and the binder.
- Carbon fiber mat is unwoven automatically during mixing to make fibers disperse.
- Good dispersion of carbon fibers is gained in various cement-based composites.

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ABSTRACT

The carbon fiber mat was first manufactured in the laboratory by means of the following procedure: dispersing chopped carbon fibers in the dispersant solution with the concentration of 0.4%, separating carbon fibers from the dispersant liquid using the thin gauze, and depriving the dried fiber mat from the gauze. The mat was then used to prepare carbon fiber reinforced cement-based composites (CFRCs) directly. Once the mat was mixed with water and cement, the adhesion between fibers would fail because of the water-solubility of the dispersant (also worked as the binder in the dry mat), leading to the mat unwoven and fiber dispersion into the cement matrix. To develop this method, different types of dispersant and carbon fibers were combined to prepare carbon fiber mat. Effective dispersion of carbon fibers in cement matrix has been obtained. Further, the applicability of this method has been proved to prepare CFRCs containing coarse aggregate, varying concentrations of carbon fibers, and carbon black. It was shown that the percolation threshold of CFRCs was about 0.6–0.9 vol.%, and CFRCs containing 0.3 vol.% of carbon fibers and not less than 0.6 vol.% of carbon black possessed low resistivity and good mechanical properties.

1. Introduction

Carbon fiber reinforced cement-based composites (CFRCs) carrying chopped carbon fibers has gained attentions for their possible applications to structural sensing and electrical actuation. That is, it can not only sense compressive or tensile stress and strain, damages and temperature [1–5], but also be used as a type of conductive concrete to melt snow or deice for highways, or be used to shield the electromagnetic waves [6–8]. However, as received carbon fibers often form agglomerates. It is still a troublesome work to disperse chopped carbon fibers in cement-based materials uniformly because of their hydrophobic surface. Poor dispersion of carbon fibers will induce low mechanical properties, unstable electrical properties of CFRCs and poor reproducibility of cement-based strain sensors and cement-based thermocouples [9,10].

Some methods to disperse carbon fibers in cement-based materials have been reviewed by Chung [11]. The common method to disperse carbon fibers in cement matrix included three steps. First, unsized carbon fibers were treated with ozone, nitric acid, silane or sodium *n*-dodecyl sulfate (SDS), etc. to improve the hydrophilcity of carbon fibers [12]. Second, carbon fibers were mixed with water containing dispersant such as cellulose and acrylic, etc. [13,14]. The addition of cellulose could improve the viscosity of water and decrease the surface tension of water. Usually, the dosage of the cellulose was close to that of carbon fiber. Finally, fibers and other materials were mixed. However, in this way the volume of water was not enough to provide room for carbon fiber dispersion. Some methods for evaluation of fiber dispersion have also been studied. Shui and Stroeven [15] used impedance measurements to assess the uniformity of carbon fiber dispersion in cement paste. Ozyurt et al. [16] investigated the ability of AC-impedance spectroscopy to non-destructively monitor the fiber dispersion in CFRCs. Yang [17] has developed the fresh mixture method for evaluation of

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fiber dispersion. Wang et al. [18] have put forward to a dispersion index based on X-ray CT images of CFRCs to evaluate fiber dispersion quantitatively.

The objective of this study is to develop a novel method to disperse carbon fibers in cement-based composites. Six types of the carbon fiber mat were first prefabricated in the laboratory by combining three types of carbon fibers and two types of dispersant. Then they were used to prepare CFRCs. Effects of the different mat on mechanical and electrical properties of CFRCs were investigated. The degree of carbon fiber dispersion in cement matrix has been evaluated. To further verify this method, CFRCs containing different contents of carbon fibers was prepared by using the prefabricated carbon fiber mat. Percolation threshold, referred to the volume fraction above which the fibers touch one another to form a continuous electrically conductive path [19], was obtained and compared with the value reported in pervious studies. The aim to develop this method is to manufacture conductive concrete on a large scale for melting snow and deicing on highways. To decrease the cost of conductive concrete, part of carbon fibers was replaced by the conductive high-structure carbon black. So, in the final part of this paper, properties of carbon fiber/carbon black reinforced concrete (CFCBRC) were studied. If only conductive carbon black is used, the mechanical properties of conductive concrete cannot satisfy the requirements for building highways.

2. Experimental procedure

2.1. Raw materials

Carboxymethylcellulose sodium (CMC) from Sinopharm Chemical Reagent Ltd. Co. (Shanghai, China) and hydroxypropyl methylcellulose (HPMC) from Shanghai Comfull Chemicals Ltd. Co. were used as the dispersant, respectively. Their basic parameters are listed in Tables 1 and 2, respectively. Three types of PAN (polyacrylonitrile)-based carbon fibers, produced by Zoltek Ltd. Co., Shanghai Carbon Ltd. Co., and Tairyfil Formosa Plastics Co., respectively, were employed. The nominal length of carbon fibers was 6 mm. The properties of carbon fibers are listed in Table 3. The high-structure carbon black from Huaguang Chemical Plant (Shandong, China) was also used as a conductive admixture. The main properties of carbon black are given in Table 4. A kind of dispersant (DA-1) prepared by authors was used to disperse carbon black in water. Cement used was Portland cement (P.O.42.5) from Huaxing Cement Ltd. Co. (Hubei, China). Water-reducing agent (WA) was naphthalene-based superplasticizer (Haoyuan Chemical Co, Hubei, China). The local fine aggregate (maximum particle diameter of 1.25 mm) and coarse aggregate (maximum size of 12 mm) were used.

Table 1
The basic coefficients of CMC.

Items	Content of Na (%)	Content of chloride (%)	pH (10 g/L, 25 °C)	Viscosity (20 g/L, 25 °C) (MPa s)	Loss on drying (%)
Value	6.5–8.5	⩽3.0	6.0–8.5	800–1200	⩽10

Table 2
The basic coefficients of HPMC.

Items	Methoxyl content (%)	Hydroxypropyl content (%)	pH (10 g/L, 25 °C)	Viscosity (20 g/L, 25 °C) (MPa s)	Loss on drying (%)
Value	19.0–24.0	4.0–12.0	5.5–7.5	20,000	⩽6

Table 3
Properties of carbon fibers.

Type	Diameter (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Resistivity (Ω m)	Density (g cm^{-3})
CF-Shanghai	7.0	⩾1950	⩾175	2.50×10^{-5}	1.75
CF-Tairy	7.0	4000	240	1.90×10^{-5}	1.80
CF-Zoltek	7.0	3800	228	1.55×10^{-5}	1.81

Table 4
Main properties of carbon black.

Resistivity (Ω cm)	Specific surface (m^2/g)	Particle size (nm)	The pH scale
0.22	1056	33	8.0

Fig. 1. The strainer for separation carbon fibers from the dispersant solution.

2.2. Preparation of the carbon fiber mat

First, the dispersant was dissolved in the hot water of about 80 °C. Then, the solution was diluted with the tube water until the concentration of the solution was 0.4% (by mass). The temperature of the solution was about 25 °C. After that, carbon fibers were added and mixed for about 5 min manually. 10 g of carbon fibers was added into 25 L of the solution to ensure carbon fibers to disperse in the solution completely. Then, the solution was poured into a strainer to separate carbon fibers from the dispersant liquid. As shown in Fig. 1, the top of the strainer is a sieve covered with a layer of wet gauze, and the bottom of the strainer is a container. The left solution in the container could be used repeatedly. After that, the gauze was laid on the floor, and dried in the air for 24 h (See Fig. 2). After dried, the carbon fiber mat was deprived from the gauze. The finish product of carbon fiber mat (1 m × 1 m) is shown in Fig. 3. Basic coefficients of the mat were: the area density 11 g/m^2; the content of dispersant 10%. As shown in Fig. 4, the self-made carbon fiber mat is interwoven by numerous single carbon fiber. The photo was taken using the optical microscope, Keyence VHX-600E. In this study, two types of dispersant such as CMC and HPMC and three types of carbon fibers from Shanghai, Tairy and Zoltek, respectively, were combined so that six types of carbon fiber mat were prepared.

2.3. Preparing CFRCs using the carbon fiber mat

For large-scale preparation of CFRCs, at first, the mat will be mixed with a portion of cement and small amount of water to let it break up into carbon fiber patches with different size and shape. Then other materials will be added and stirred. Since only small-scale preparation of CFRCs was performed in the laboratory, so the mat was broken up into carbon fiber patches manually. First, small amount of water was sprayed on the mat. Its aim was to dissolve the dispersant in the mat, which was worked as the binder in the dried mat, and to facilitate the mat to be separated. Then, the mat was covered with a thin layer of cement. Its purpose was to bond one thin layer of cement on the mat, which could separate adjacent carbon fiber patches. The quantity of water sprayed on the mat could make cement half-dry. The mat was then divided into small patches with different shapes by