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# Dispersion of carbon fibers and conductivity of carbon fiber-reinforced cement-based composites

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ABSTRACT

Dispersion of carbon fibers in the cement matrix remains a hot topic in the preparation of carbon fiber-reinforced cement-based composites (CFRC) because it affects greatly both the mechanical and electrical properties of the composites. In this work, a new dispersant hydroxyethyl cellulose was used with the aids of pre-dispersion by ultrasonic wave to realize the uniform distribution of chopped carbon fibers in the cement matrix. The fracture surface of the prepared CFRC was observed by scanning electron microscopy, the elemental distribution was investigated by energy dispersive spectroscopy, and the components was analyzed by X-ray diffraction. Influences of carbon fiber lengths and contents, water/cement weight ratio, molding process, curing time, and silica fume content over the conductivity of the CFRC composites were studied. The mechanism of conductivity was discussed. Results shown that the electrical resistivity intended to decrease with the increasing of carbon fiber contents. The mass fraction 0.6% of carbon fibers was a turning point. The concentration of hydroxyethyl cellulose between 1.66% and 1.86% was mostly beneficial for the dispersion of carbon fibers. The resistivity was increased first and decreased then with the increase of water/cement ratio. When the CFRC sample was prepared by the vibrating pressing method, the resistivity of the sample was reduced far greatly than that of the sample by the vibrating method. The incorporation of silica fume into the CFRC composites exerted not only a good effect on the dispersion of carbon fibers, but also increased the density of the composites to further influence the conductivity of the CFRC.

## 1. Introduction

Cement is a construction material commonly used in engineering constructions due to its rich resources, good environmental adaptability, low cost and high compressive strength [1–6]. It self is an electrical insulating material. Carbon fibers exhibit a series of outstanding properties of high strength, high modulus, high temperature resistance, corrosion resistance, fatigue resistance, creep resistance, light weight, and electric conduction [1,3,7–9]. It is convenient to produce carbon fiber-reinforced cement-based composites (CFRC) [6,10–12] by adding short carbon fibers into cement matrix. In the CFRC composites, carbon fibers are advantageous in their superior ability to increase the tensile strength of cement. They can improve both mechanical and electrical behaviors of the material as well as the electromechanical and electromagnetic behaviors [1,13–15]. They are also advantageous in the relative chemical inertness. In relation to most functional properties, carbon fibers are exceptional compared to other fiber types [1,3].

CFRC is of great technological interest owing to the combination of good structural properties and exceptional electrical properties. It can be used both as structural materials and as functional materials. The electrical resistivity of CFRC has been widely studied because of its utility as multifunctional materials [16,17]. Its applications, particularly in military use, have attracted more and more researchers' attention and become a hot topic for the cementitious materials [1,6,9]. The incorporation of an appropriate amount of carbon fibers into cement matrix can not only enhance the tensile ductility, flexural strength, and toughness to reduce the dry shrinkage and to improve the bond strength of CFRC, but can also adjust the electrical conductivity in a large range [18,19]. Meanwhile, CFRC is more attractive for its multifunctional behavior, which derives from its electrical property, including strain sensing, temperature sensing, piezoresistivity effect, thermoelectric effect, and joule heating [1,20–22]. It special features involves pressure sensitivity, thermoelectric effect, Joule effect, low drying shrinkage, high specific heat, low thermal conductivity, high electrical conductivity, high corrosion resistance and weak thermo-

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electric behavior, and temperature resistance effect [23,24]. Therefore, it is a kind of promising materials in the engineering fields of civil engineering, industrial anti-static, health monitoring, non-metal heating elements and buildings against electromagnetic wave shielding [19,25,26].

The effect of carbon fiber addition on the properties of cement increases with the fiber content, unless the content is so high that the air void content becomes excessively high. The air void content increases with the fiber content and the air voids tend to have a negative effect on many properties, such as the compressive strength. In addition, the workability of the mix decreases with the fiber content. Effective use of carbon fibers in cement requires their homogeneous dispersion in the cement matrix [6,27,28].

There are lots of factors affecting the properties of CFRC composites. Among them, the dispersion of carbon fibers in the cement matrix directly affects the mechanical properties and electrical properties. In order to make carbon fibers uniformly dispersed in the cement matrix, an appropriate amount of suitable dispersants and additives [29,30] should be added in the preparation of CFRC composites. The dispersion is also enhanced by using silica fume (a fine particulate) as an admixture. A typical silica fume content is usually 15% by weight of cement [31,32]. Silica fume is typically used along with a small amount (0.4% by weight of cement) of methylcellulose for helping the dispersion of fibers and the workability of the mixture [33,34]. The improved structural properties rendered by carbon fiber addition pertain to the increased tensile and flexible strengths, the increased tensile ductility and flexural toughness, the enhanced impact resistance, the reduced drying shrinkage and the improved freeze-thaw durability [35,36].

The fiber dispersion greatly affects the air void content, which in turn exerts influence on the mechanical and electrical performances of the CFRC composites [34,37,38]. Many works have been done on the electrical properties of CFRC as of today [1,16,39–41]. However, the relationship between carbon fiber dispersion and conductivity of CFRC has been little reported yet.

With this in mind, in the present work, carbon fibers were firstly dispersed in the aqueous solution with the aids of a good dispersant hydroxyethyl cellulose. The dispersed system was then incorporated into the cement matrix under moderate stirring to ensure carbon fibers were uniformly dispersed to have achieved homogeneous CFRC samples. The flexural strength and the compressive strength of the samples were tested. The fracture surface of the samples were observed by scanning electron microscopy. The distribution of major elements in the CFRC was analyzed by energy dispersive spectroscopy (EDS). The composition of CFRC was analyzed by X-ray diffraction (XRD) at different amounts of carbon fibers. The resistance was measured to further calculate the resistivity. Influences of carbon fiber contents and lengths, water/cement ratio, curing age, molding process, and content of silica fume on the conductive properties of CFRC composites were investigated. The experimental results and theoretical analysis may provide helpful references for CFRC used as functional materials both for civilian and military purposes.

## 2. Raw materials and experimental methods

### 2.1. Major raw materials

Short carbon fibers used were polyacrylonitrile-based 5–7 mm in length provided by Jiyan Carbon Co., Ltd. (Jilin, China). Their major parameters are shown in Table 1. The matrix was 32.5R Portland cement with the execution standard GB175-1999 from Qinling Cement Plant, Shaanxi, China. The water/cement ratio was from 0.3 to 0.5. The mass fractions of carbon fibers by weight of cement were 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%, respectively. No aggregate (fine or coarse) was used.

The dispersants used were hydroxyethyl cellulose made in Shandong Yiteng Chemical Co., Ltd with the viscosity of 30000 Pa.S. The mass fraction of hydroxyethyl cellulose was in the amount of 0.6% by mass of cement. Silica fume (300 mesh, purity 99.7%, Kaihua Yuantong Silicon Industrial Co., Ltd, Zhejiang) was used in the amount of 5%, 10%, and 15% by mass of cement. The diameter of silica fume particles ranges between 0.01 and 0.1 μm.

Naphthalenesulfonate formal condensate, a water-reducing agent, purchased from Wuhan Iron and Steel Corporation Admixture Factory was used in the amount of 0.8% by mass of cement. The defoamer was liquid tributyl phosphate (Henghao Science and Technology Co., Ltd, Tianjin, China), which was used in the amount of 0.02% by mass of cement. A DDG-A high efficiency electric contact conductive paste was made in Wuhan Changjiang Mechanical and Electrical Equipment Industrial Co., Ltd.

### 2.2. Preparation of CFRC samples

To prepare homogenized CFRC samples, the dispersion of short carbon fibers are divided into two steps. In the first step, they are dispersed into the aqueous solution, and in the second step they are distributed in the solid mixture.

Carbon fibers were first placed in a 500 mL glass beaker. About three-fifth of the entire water to be used in the subsequent test was added to make sure that carbon fibers were immersed fully into water. The beaker was vibrated by ultrasonic wave for 10 min for pre-dispersion. The temperature of the water was kept between 38 and 44 °C. The power of the ultrasonic wave was 250 W. Hydroxyethyl cellulose, a dispersant, was dissolved in water and stirred by hand for 2 min. Two drops of tributyl phosphate were added to eliminate air bubbles. The beaker was continuously vibrated by ultrasonic wave for another 10 min. The dispersion process can be seen clearly through the transparent glass beaker. In the first step, the mass fraction of hydroxyethyl cellulose in the aqueous solution was controlled between 1.66% and 1.86%. A glass rod was used to stir carbon fibers intermittently to ensure their uniform dispersion in the transparent, sticky solution. No breakage of carbon fibers occurred during the ultrasonic vibration. This is the first step for the dispersion of carbon fibers.

Now comes to the second step. Silica fume, cement, standard sand, naphthalenesulfonate formal condensate, and other additives were mixed in a J-160A rotary mixer with a flat beater for 2 min. Then, the prepared liquid dispersive system in the first step was poured into the mixer. The left two-fifth of water was added and mixed for another 2 min. The mixture was stirred for 1 min quickly.

By these two steps, carbon fibers are well dispersed in the prepared hardened CFRC samples, though the mixing and later molding operations might change the dispersion degree more or less.

After pouring the prepared mixture above into the rectangular oiled moulds of 160 × 40 × 40 mm and the cube oiled moulds of 40 × 40 × 40 mm, respectively, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. For the rectangular beam, three samples of each mix were prepared for flexural strength and compressive strength test. For the cube block, thin sheets

**Table 1**
Main parameters of short carbon fibers.

| Diameter/μm | Density/g/cm$^3$ | Tensile strength/MPa | Shear strength/MPa | Elastic modulus/GPa | Elongation/ % | Electrical resistivity/Ω·cm |
|---|---|---|---|---|---|---|
| 7 ± 0.2 | 1.76–1.78 | 2500–3000 | 80 | 200–220 | 1.25–1.5 | $3.1 \times 10^{-3}$ |