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Reinforcement effect and mechanism of carbon fibers to mechanical and electrically conductive properties of cement-based materials

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HIGHLIGHTS

- Carbon fibers with hydrophilic surface were used to reinforce cement mortar.
- Ultrasonic treatment fibers can obviously enhances the properties of cement mortar.
- Enhancing mechanism is analyzed through microstructure observation and calculation.

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ABSTRACT

In this paper, carbon fibers with hydrophilic surface modification were added into cement mortar through ultrasonic treatment. The mechanical and electrical properties of carbon fiber filled cement mortar were tested to examine the reinforcing effect of carbon fiber. In order to understand the underlying modification mechanisms of carbon fibers to cement mortar at micro scale and in theory, scanning electron microscope (SEM) observation and theoretical calculations were carried out. Test results indicate that the adding of carbon fibers into cement mortar enhances the mechanical strength (especially compressive strength), and decreases the electrical resistivity of carbon fiber filled cement mortar. SEM results show that the enhancement of the properties of carbon fiber filled cement mortar owes to fiber ability of restraining the growth of microcracks and absorbing energy by overcoming its pulling out. The enhancing mechanism of carbon fibers on the properties of cement mortar analyzed by the calculated fiber numbers per unit volume, average center distance between two carbon fibers and the critical pull-out length well matches the experimental results.

1. Introduction

As a new generation of reinforcing fiber of cement-based composite, carbon fibers have many well-known properties such as low density, low heat transfer coefficient and expansion coefficient, high tensile strength, corrosion resistance, good toughness and durability, good chemical stability and heat conduction performance [1–9]. In addition, carbon fibers with different volume fractions not only can obviously improve the mechanical properties, enhance the capacity of deformation and control the growth of cracks, but also expand the application scope of cement-based materials by giving some functional or intelligent features to carbon fiber reinforced cement composites (CFRC) [3,10,11].

The literature has a considerable amount of work on mechanical properties of CFRC. Toutanji et al. [6] studied that the addition of 1%, 2% and 3% vol of carbon fiber to cement matrix results in an increase in the flexural strength of 72%, 95% and 138%, respectively. Park et al. [12] mixed the carbon fiber loading of 1 vol%, 2 vol% and 3 vol% with cement mortar. Test results showed that 14d tensile strengths of cement mortar with 1 vol%, 2 vol% and 3 vol% carbon fiber increased by 103%, 172% and 255% than that of ordinary cement mortar, respectively. Xu et al. [13] observed that the tensile strength of cement paste was increased by 56% and the modulus and ductility were increased by 39% by using silane-treated carbon fibers and silane-treated silica fume, relative to the values for cement paste with as-received carbon fibers and as-received silica fume. In addition, the toughening effect of carbon fiber on cement-based material matrix and constitutive relation under cyclic loadings were studied by Deng et al. [14].

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Effect of carbon fiber on electrical property of CFRC has also been studied. It is found that the conductive mechanism of CFRC was tunnel conductive effect [15–17]. Chen et al. [18] studied the influence of carbon fiber volume, size, cement-based matrix, relative humidity and curing age on the characteristic of the system and investigated the percolation phenomenon by using scanning electron microscope (SEM). Manuela et al. [19] studied the effect of the carbon fiber length and volume fraction on the resistivity of CFRC. Test results indicated that the resistivity of CFRC decreased as the length of carbon fiber increased. The results of Chung [20] showed that the change of volume resistivity was linked with the closure and development of internal cracks and the interface contact state between carbon fiber and cement-based composites. In addition, Chen et al. [21] examined the effect of different carbon fiber contents on pressure sensibility of CFRC and built up the model of relationship between resistance and strength. Besides, it is found that the health monitoring of civil engineering structure, stress/strain sensor, self-sensing and self-diagnosis could be achieved by smart CFRC [22–26].

Most previous work examine the effects of carbon fiber on cement-based materials, but it is found that compressive strength is not improved obviously and even is decreased. However, in this paper, we use fiber hydrophilic surface modification and ultrasonic treatment methods to effectively disperse carbon fibers in cement mortar, and investigate the effects of carbon fiber on the properties of cement mortar with 84 carbon fiber filled cement mortar specimens. Meanwhile, the results calculated with theoretical analysis have been compared to the experimental results. As a result, the mechanical and electrical properties have been improved, especially the compressive strength is enhanced obviously.

2. Experimental

2.1. Materials

In this research, 3 mm and 6 mm PAN-based carbon fibers with hydrophilic surface modification, made in Jilin Chemical Industry Co. LTD, are used. The performance parameters of carbon fibers are shown in Table 1. P.O 42.5R Portland cement (Dalian Onoda Cement Co. Ltd., China) was applied as binder materials. Standard sand (Xiamen Ai Si Ou Standard Sand Co. Ltd., China) was used as fine aggregate. The water reducer is 3310E polycarboxylate superplasticizer provided by Dalian Xi Ka whose solid content is 45% and can reduce water to an extent of 30%. In addition, densities of raw materials are shown in Table 2. Stainless steel gauzes with opening of 50 mm × 50 mm were used as electrodes whose length and width are 10 and 6 whole grids, respectively [27].

2.2. Sample preparation

A total of 13 cement mortar mixes containing five components, namely cement, water, sand, water reducer and carbon fibers, were prepared. The water/cement ratio is fixed at 0.38. Carbon fiber loadings of 0, 0.2, 0.5, 0.8, 1.1, 1.5 and 2.0 percent per mass of cement were used to fabricate the carbon fiber filled cement mortar. The dosage of water reducer increases with the increase of the dosage of carbon fibers to ensure necessary fluidity for specimen molding. The mix proportions of carbon fiber filled cement mortar show in Table 3. There were 6 specimens for each mix proportion. Three of them (marked as Sample-1-3d, Sample-2-3d, and Samples-3-3d) are for the performance test at 3d, and others (marked as Sample-1-28d, Sample-2-28d, and Samples-3-28d) are for the performance test at 28d. As presented in Fig. 1, the detailed manufacture process of carbon fiber filled cement mortar is as following:

(1) Mix the water reducing agent and water in the beaker with vibrating.
(2) Add carbon fibers into the water reducing agent/water solution and then put it in ultrasonicator (Branson 2510 E-DTH, 100 W 42 KHz, Bransonic Ultrasonics Corporation, USA) for half an hour to get uniform suspension.
(3) Put the suspension into sand mixer provided by Chinese Yu Hua Instrument Ltd, and then stir at low speed for 60 s and pour the cement into the suspension slowly and evenly during this 60 s, finally agitate the cement past at fast speed for 30 s.
(4) Add the sand into sand mixer during the first 60 s at low speed and then agitate it at high speed for 30 s. After that, agitate for another 90 s.
(5) Put the uniform cement mortar into the oiled mould (40 mm × 40 mm × 160 mm) and vibrate for 20 s.
(6) Embed two stainless-steel-wire-electrodes at both position 10 mm far away from the sides (as shown in Fig. 2) and vibrate for another 5 s.
(7) Demould specimens after curing the temperature humidity chamber (20.0 °C and 95% relative humidity) for 24 h.
(8) Cure the specimens in water at 20 ± 2°Cuntil test flexural and compressive strengths at 3d and 28d.

2.3. Measurement

The flexural strength was measured by using the mortar folding meter DKZ-5000 provided by Wuxi Jianyi Instrument & Machinery Co., Ltd. The compressive strength was measured by universal testing machine WDW-200E (Jinan Times Shijin Test Machine Co., Ltd). The compressive strengths of specimens were tested in displacement-controlled mode with a displacement rate of 1.2 mm/min. Resistance of the specimens without loading were tested by a two-electrode method by using a handheld LCR meter (U1733C, Agilent Technologies, Inc., USA) with 0.2% of measuring accuracy. Field Emission Scanning Electron Microscope (Nova Nano SEM 450, American FEI Ltd) was used to observe the morphology of the carbon fiber filled cement mortar.

Table 1
Physical properties of carbon fiber.

Diagram (μm)	Tensile strength (MPa)	Tensile modulus (GPa)	Density (kg m^{-3})
7	3450	230	1800

Table 2
Densities of raw materials.

Raw materials	Cement	Sand	Water	Water reducer
Density (kg m^{-3})	3100	2650	1000	1100

Table 3
Mix proportion.

NO.	Cement (kg m^{-3})	Water (kg m^{-3})	Sand (kg m^{-3})	Water reducer (kg m^{-3})	Carbon fiber (kg m^{-3})
0	545	207.1	1653	0 (0%)	0 (0%)
1	545	207.1	1653	0.5450 (0.1%)	1.090 (0.2%)
2	545	207.1	1653	0.8175 (0.15%)	2.725 (0.5%)
3	545	207.1	1653	2.3980 (0.44%)	4.360 (0.8%)
4	545	207.1	1653	2.7250 (0.50%)	5.995 (1.1%)
5	545	207.1	1653	3.2700 (0.60%)	8.175 (1.5%)
6	545	207.1	1653	3.8150 (0.70%)	10.900 (2.0%)