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Mechanism and strengthening effects of carbon fiber on mechanical properties of cement mortar

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***Keywords*— Carbon Fiber, Cement-Mortar, Polycarboxylate, Superplasticizer, Fluidity, Strength**

***Abstract*— *Carbon fibers have many advantages, such as low density, low heat transfer and expansion coefficients, high tensile strength, and good chemical stability and thermal conductivity. Aiming to improve the properties, this study investigates the effects of adding different amounts of carbon fiber to cement mortar. First, a fluidity test was performed to determine the effects of different carbon-fiber contents on the fluidity of cement mortar. Thereafter, the effects of the amount of carbon fiber on the flexural and compressive strengths of cement mortar were investigated under consistent fluidity conditions by adding a polycarboxylate superplasticizer. The interfacial transition zone of the carbon-fiber-modified cement mortar and the microstructure and morphology of the hydration products were observed via-scanning electron microscopy. Furthermore, the influence of carbon fibers on the mechanical properties of cement mortar and the associated mechanism were studied.*

I. INTRODUCTION

The inherent brittleness of cement based materials owing to low tensile strength and poor fracture toughness limits their structural design and long-term durability. The incorporation of fiber into cement mortar has received extensive research attention as it can significantly improve the tensile strength and fracture toughness as well as reduce various defects. Carbon fibers have low density, low heat-transfer and expansion coefficients, high tensile strength and corrosion resistance, and good toughness, durability, chemical stability, and thermal conductivity [1]. Therefore, carbon fibers incorporated into cement-based materials can significantly improve the mechanical properties, enhance the deformation ability, and control the propagation of cracks. Extensive studies have been conducted on the properties of cement-based materials doped with carbon-fibers. Khaleel et al [2]. Found that the addition of 1% CFC to cement mortar resulted in a higher compressive strength under fire and high-temperature conditions. Studies have shown that the strategic application of carbon nanofibers considerably densifies the interfacial transition zone (ITZ) and significantly reduces voids and defects. It has better mechanical properties against deformation and cracking, thereby enhancing the fiber/matrix bonding and improving the load transfer efficiency between the fiber and the matrix. Chen B[3] studied the effects of carbon-fiber volume, size, cement-based matrix, relative humidity, and curing age on the electrical conductivity of carbon-fiber cement-based materials .Nan et al .[4] studied the electrical conductivity and mechanism of cement paste and carbon-fiber cement-based composites with different carbon fiber and aggregate contents and found that the resistivity of carbon-fiber cement-based composites decreased under compression owing to the difference between the matrix and fiber; compared to the individual components, the composite exhibited improved interfacial contact and an increased probability of fiber bridging. Fiber pullout and breakage under tension results in an increase in the resistivity of composites. Furthermore, aggregates hinder fiber dispersion and contact and result in an increase in the resistivity of composites. Zamir M [5] found that a hybrid coating of carbon-fiber fabrics significantly improved the mechanical properties of composites through the pozzolanic reaction at the fabric–substrate interface.Al-

SaadiN.T.et al.[6] used the finite element method to simulate the bonding behavior between NSM CFRP tape and a cement-based adhesive concrete substrate. Toutanji et al.[7] found that adding carbon fibers with volume fractions of 1%, 2%, and 3% to a cement matrix increased the uniaxial tensile strength by 32%, 48%, and 56%, respectively, and the flexural strength by 72%, 95%, and 138%, respectively. Hossain et al. [8] found that a combination of 3 mm (0.12in) and 6 mm (0.36in) fibers enhanced the crack resistance, ultimate stress, and Young's modulus of fiber-reinforced cement composites. XuY. [9] Used silane-treated carbon fibers and silane-treated silica fume to increase the tensile strength by 56% and the Young's modulus and ductility by 39%.

Herein, the effects of carbon fiber on the mechanical properties of cement mortar were investigated by adding different amounts of carbon fiber to cement mortar. Subsequently, the ITZ of the carbon-fiber-modified cement mortar and the microstructure and morphology of the hydration products were observed via-scanning electron microscopy (SEM).

II. MATERIALS

Raw Materials:

Portland PO 42.5 cement produced by Taiyuan Co.Ltd.based on the relevant Chinese standard was used. The details of the carbon fiber are presented in Table1. A photograph of the carbon fibers is shown in Fig.1, and the SEM micrographs of the carbon fibers are shown in Fig.2.The polycarboxylate superplasticizer (solid content of 20%) was customized by the manufacturer. Standard sand, which conformed to the Chinese ISO sand standard GB/T17671, was obtained from Xiamen Aisio Standard Sand Co .Ltd. Tap water was used for the experiments.

Length (mm)	Single wire diameter (μm)	Strength (MPa)	Modulus (GPa)	Elongation (%)	Linear density (g/m)
6	7.76	>3000	>2100	1.9	1.7

Fig1. Photograph of carbon fibers

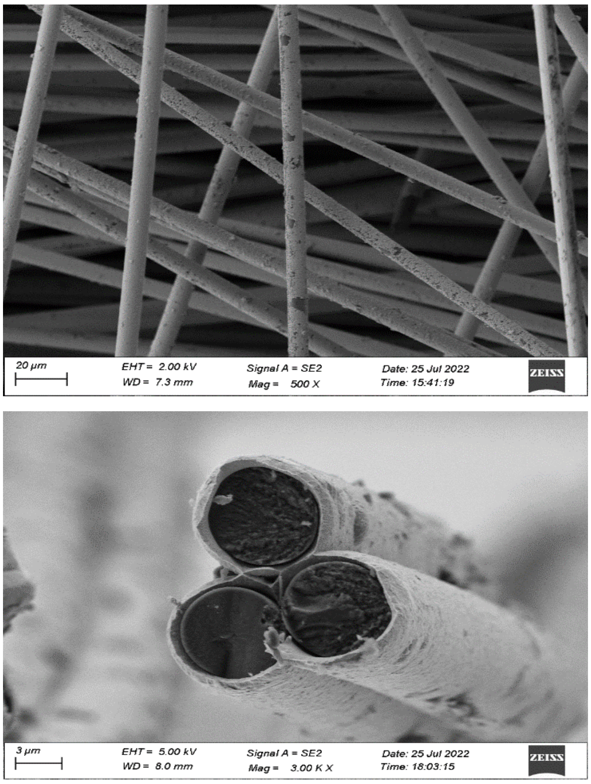


Fig 2.Microstructure of the carbon fibers

III. EXPERIMENT

Cement mortar fluidity test and mix ratio selection

A fluidity test was performed in accordance with GB/T2419-2005 using a jumping table to measure the consistency and work ability of newly formulated mortar. The poly-carboxylate superplasticizer content in the cement mortar was determined by performing a fluidity test.

Preparation of cement mortar samples

Cement mortar samples with different contents of carbon fibers were prepared. The mixing proportions of the samples are listed in Table 2; the water: cement ratio is 0.4, and the cement: sand ratio is 1:2.The dosage of the water reducer was increased with an increase in the dosage of carbon fibers to a consistent fluidity for each cement mortar sample. Sample M is plain cement mortar. MCFn is cement mortar mixed with a certain amount of carbon fiber, where n denotes that the carbon fibers accounts for one-thousandth the weight of the cement. For example, MCF4 represents a mixed cement mortar with 0.4% carbon fiber with respect to the cement weight.

The cement mortar was prepared as follows:

–The carbon-fiber mixed solution and cement were added to a mixing pot, and the pot was placed on a fixed frame. The mixture was mixed at a low speed for 30s. Standard sand was evenly added via a mixing funnel after 30s, and the mixture was then mixed at a high speed for 30s.

–After the mixer stopped, any material that collected on the side of the bowl was immediately scraped down into the batch. Thereafter, the mixer enclosure was closed, or the bowl was covered with a lid, and the paste was left to stand for 90s.

–The mixture was mixed for 60 s at a high speed.

–The fresh cement mortar was poured into a steel mold and compacted using a standard vibrating table. The molds were then sealed with polyethylene nanosheets to prevent the loss of moisture. After 24h, the samples were demolded and cured in a saturated lime-water bath at 20°C for specific aging durations (3, 7, and 28 d).

Table 2 Mixing proportions of carbon-fiber-modified cement mortar samples

Sample No	Cement(g)	Sand(g)	Water(g)	Carbon Fiber(g)	SP(g)
M	675	1350	270	0	3.6
MCF1	675	1350	270	0.675	3.8
MCF2	675	1350	270	1.35	4.5
MCF3	675	1350	270	2.7	4.7
MCF4	675	1350	270	4.05	5.4

IV. MECHANICAL TEST

The flexural and compressive strengths of the specimens were determined according to GB/T17671-1999 after 3, 7, and 28 d. For each series, three specimens were tested to determine their strength. The flexural strength test was performed in a three-point bending test apparatus with a loading rate of 0.06N/s. The loading rate for the compression strength test was 2.4KN/s.

SEM characterization of hydration products

SEM (ZEISS Gemini SEM 300) was used to observe the micromorphology of the cement mortar samples at 28d. Samples with flat surfaces and small thicknesses were selected, soaked in absolute ethanol for a week, and then placed in a vacuum desiccators at 40°C. The box was then dried for 72 h .Before performing SEM, the sample surfaces were coated with a thin layer of gold.

V. RESULT & DISCUSSION

Effects of the carbon fiber on the workability of cement paste.

Fig.3 shows the fluidity of the carbon fibers. Compared with cement mortar M, when the carbon-fiber content is 0.2%, the fluidity of cement mortar decreases by 10.9%.When the carbon-fiber content is 0.6%, the fluidity of the cement mortar decreases by 18.48%. The fluidity of cement mortar decreases with an increase in the carbon fiber content [10], possibly owing to the distribution and orientation of the fibers. Therefore, the addition of a water-reducing agent to the samples ensures consistency in their fluidity values and enables the comparison of their strengths.

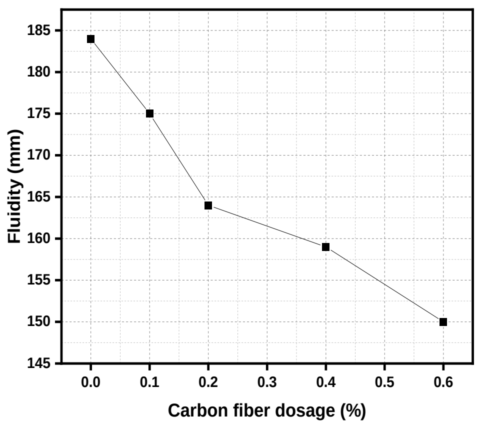
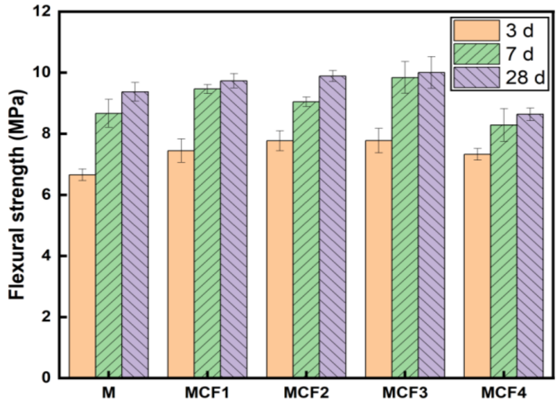


Fig.3 Fluidity of the cement mortar samples Mechanical strength of carbon-fiber-modified cement mortar

Fig.4 (a) shows the flexural strength of the cement mortar mixed with different amounts of carbon fiber at 3, 7, and 28d. The flexural strength of cement mortar gradually increases with an increase in the carbon-fiber content. However, after an optimal carbon-fiber content, the flexural strength starts decreasing. When the carbon-fiber content is 0.4%, the flexural strength of the cement mortar mixed with carbon fiber is at the highest. At curing ages of 3, 7, and 28 d, the flexural strength of Sample MCF4 increases by 16.82%,13.49%, and 7.78%, respectively, compared with that of plain cement mortar Sample M because the high strength of carbon fiber improves the mechanical properties of the cement mortar. When carbon-fiber composites are subjected to an external pressure, cracks are developed. Owing to their high tensile strength, the carbon fibers at both ends of a crack do not break immediately, and the reinforcement mechanism is mainly the crack-resistance mechanism of the fiber. The carbon fiber resists crack formation and improves the mechanical properties of the carbon-fiber cement-based composite. Under tensile stress, the fibers transfer stress to their ends, thereby reducing the stress concentration in the crack zone and allowing the sample to with stand the applied load [8]. When the amount of carbon fiber is very high, the dispersion of the carbon fiber is very uneven, resulting in a decrease in the strength of the material. The flexural strength of the cement mortar mixed with the carbon fiber continues to increase with an increase in the curing age because of the gradual increase in the degree of hydration of the cement mortar over time.



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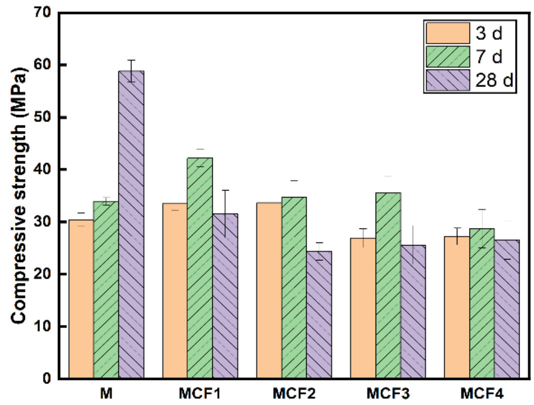


B

Fig.4.Strength of 6 mm carbon-fiber-modified cement mortar at 3, 7, and 28 d: (a) flexural strength and (b) compressive strength

Fig. 4(b) shows the compressive strength of the cement mortar mixed with different amounts of carbon fiber at 3, 7, and 28 d. When the curing ages are 3 and 7 d and the carbon-fiber content is 0.1% (SampleMCF1), the compressive strengths of the cement mortar are 10.02% and 24.42% higher than that of the plain cement mortar, respectively. However, when the carbon-fiber content continues to increase, the compressive strength of the cement mortar does not increase and is lower than that of the plain cement mortar. The reason for this phenomenon is the uneven distribution of the carbon fibers and the increased porosity. At a curing age of 28 d, the compressive strength of all the mixed cement mortar samples doped with carbon fiber is lower than that of the plain cement mortar. This maybe owing to the uneven dispersion of carbon fibers that trap the flow of free water in the cement slurry, thereby reducing the degree of hydration.

SEM results

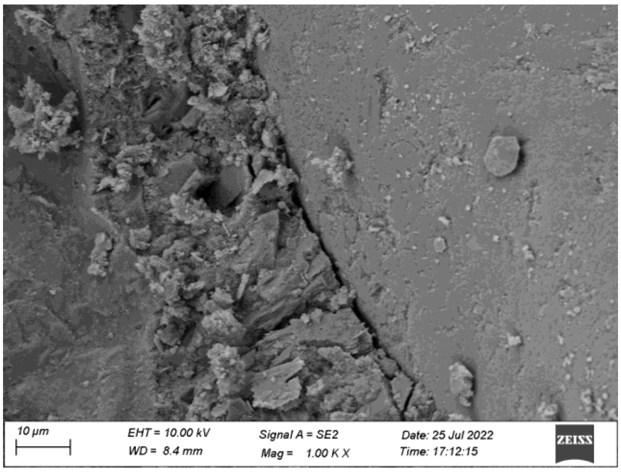
SEM analysis was performed to investigate the fiber distribution, adhesion, and failure mechanisms.

Fig. 5(A–C) show the SEM images of the plain cement mortar, revealing microstructures of the ITZ. Cracks and pores are observed in the ITZ, and a direct combination of aggregates and hydration products is not visible [11].Fig. 6(D-E) show the SEM images of cement mortar samples with 0.4% 6 mm carbon fibers. The carbon fibers are distributed in the cement matrix in the confusion. More carbon fibers are present in the 0.6% fiber sample. Therefore, an increase in the carbon-fiber content enhances the conduction of the cement mortar. However, when the carbon-fiber content reaches a certain level, the mechanical properties of the cement mortar deteriorates. The carbon-fiber content has significant effects on the mechanical properties of cement mortar [12] because the mechanical properties are sensitive to the aggregation of carbon fibers. Fig.6 (F) shows that the carbon fiber acts as a bridge and connects the cracks, indicating that the carbon fibers bond well with the cement mortar.

VI. CONCLUSION

This study showed the effects of carbon fibers on the fluidity and mechanical properties of cement mortar. Carbon fibers with lengths of 6 mm were added to cement mortar at different concentrations to prepare high-performance multifunctional cement-based composite materials. The mechanical properties of the carbon-fiber-modified cement mortar were investigated and compared with those of ordinary cement mortar. The following conclusions were drawn based on the results of this study.

The fluidity of cement mortar gradually decreases with an increase in the carbon-fiber content, which may be related to the dispersion and orientation of the carbon fibers in the cement matrix.



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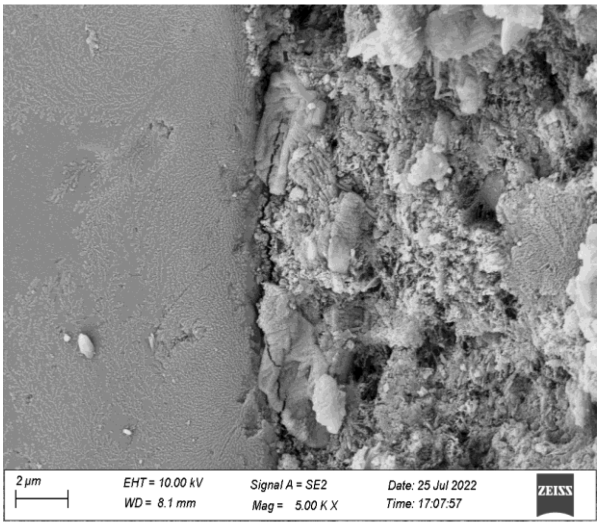

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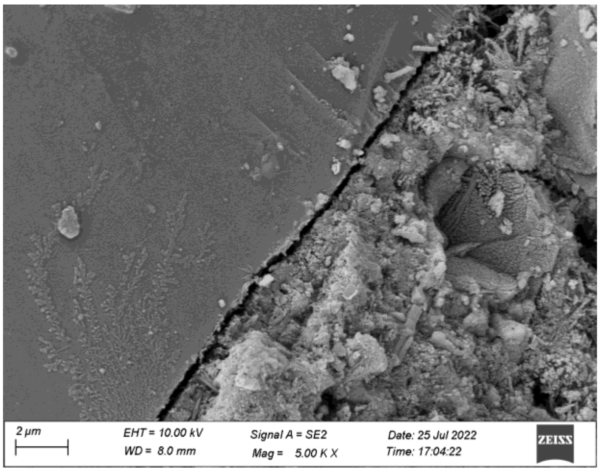

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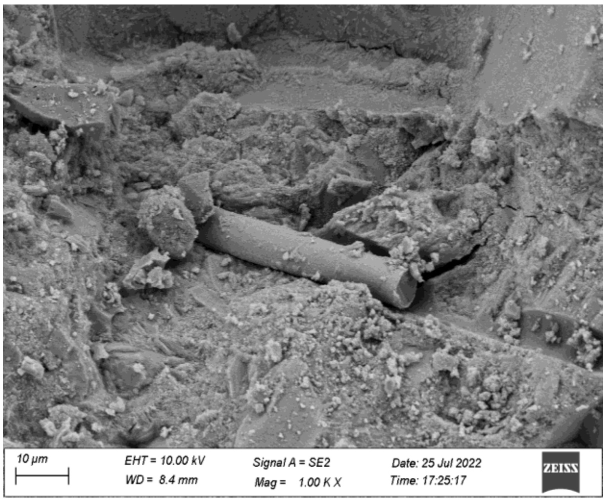
Fig 5. (A, B &C) SME images of the plain cement mortar sample



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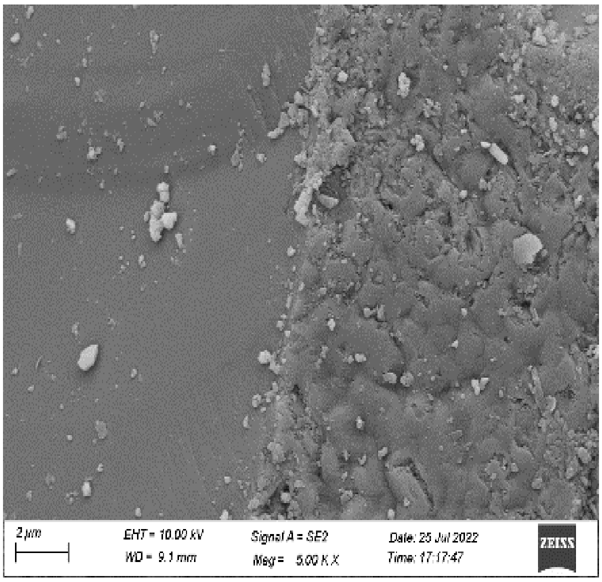

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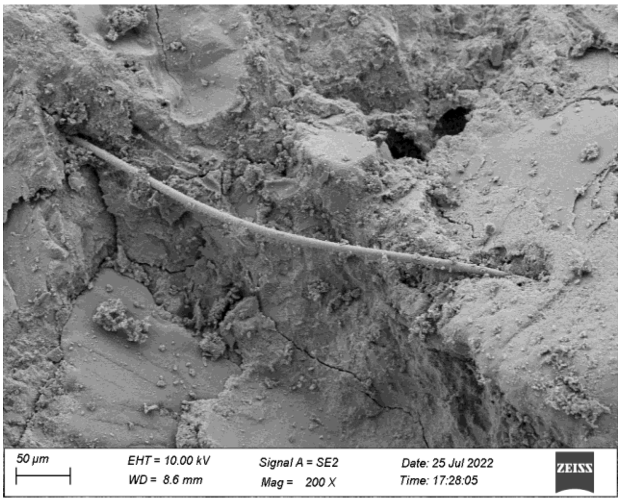

F

Fig 6. (D, E&F) SME images of the cement mortar sample containing 0.4% carbon fiber

The addition of 0.4% carbon fiber improves the strength of cement mortar. The dispersion of carbon fibers in cement mortar is sufficient to produce a high-performance carbon-fiber-modified cement mortar.

Carbon fibers are not uniformly distributed in cement mortar, and they aggregate and generate pores. Simultaneously, they may trap the free water in the cement paste, resulting in a decrease in the degree of hydration. Consequently, the reinforcing effect of carbon fibers on the cement mortar is reduced.

Carbon fibers absorb energy and overcome fiber pullout as well as inhibit the growth of micro- cracks, thereby improving the mechanical properties, particularly the flexural strength of cement mortar.

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