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Corrosion behavior of a steel bar embedded in a cement-based conductive composite

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HIGHLIGHTS

- Corrosion mechanism of rebar in cement-based conductive composite is illuminated.
- CF conductive network functions as a large anode of electrochemical corrosion.
- Percolation threshold is a critical value that determines corrosion level.

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ABSTRACT

Corrosion behavior of a steel bar embedded in a cement-based conductive composite was the object of study described in this paper. First, the conductivity percolation curve of a carbon-fiber- (CF-) reinforced cement-based composite was obtained. The dry-wet cycle method was then adopted to accelerate the corrosion of the steel bar embedded in the cement-based conductive composite. The corrosion behavior was analyzed using the linear polarization resistance (LPR) technique, the corrosion potential and the weight loss method. In addition, the effect of the CF added on the pore structure was discussed. Finally, it was found that the percolation threshold of CF in the composite is a critical value that determines the corrosion level of the steel bar. The addition of CF has no effect on the corrosion level of the steel bar at the early stage when the CF content is lower than the CF percolation threshold, while the corrosion level tends to increase when the CF content is higher than the CF percolation threshold.

1. Introduction

Cement-based composites are commonly and widely used as building materials in civil engineering projects owing to their excellent engineering properties and durability. However, they suffer from low tensile strength, are easy to crack, and have no functional properties [1,2]. The addition of carbon conductive material, such as carbon fiber (CF), carbon nanotubes (CNTs), carbon black (CB), etc., not only improves the compressive, tensile and flexural strength, the fracture resistance, and the impermeability of cement-based composites, but also imbues them with electrical, thermal and electromagnetic properties [3–7]. Thus, carbon-enhanced cement-based composites have been widely investigated to monitor the load and deformation of structures when used as a sensing material [8–13], to prevent electromagnetic interference [14,15], to deice or melt snow when used as an electrocaloric material [16–19], and to control the corrosion of reinforced concrete structure when applied as an anode overlay for impressed current cathodic protection (ICCP) in recent years [20–26]. This previous research indicates that the functional properties of cement-based composites have a close relationship with their electrical properties. For instance, when a cement-based conductive composite is used as a sensing material, the content of carbon material that approximates its conductive percolation threshold is added into the composite; when used as an anode overlay for ICCP or as an electric heating material, the electrical resistivity is as low as possible to avoid higher electrical power consumption and more rapid electrochemical consumption.

In addition, corrosion of reinforcing steel is always a prevalent issue in reinforced concrete (RC) structures since it severely degrades structural safety and durability [27], especially in areas exposed to the deicing salt or coastal marine environments [28].

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Considering that carbon-enhanced cement-based conductive composites have many such promising potential applications in civil engineering, investigating the corrosion behavior of reinforcing steel embedded in cement-based conductive composites is very necessary. However, the investigations of the corrosion behavior of a steel bar in a cement-based conductive composite have been very parse to date. Chung et al. investigated the effect of 0.5-wt% CF content on the corrosion resistance of reinforced concrete, and observed that the addition of CF had no effect on the corrosion level of the passive steel bar, but increased the corrosion level of the active steel bar [29]. Garces et al. studied the effect of the addition of different proportions of CF, CNT and graphite powder on the corrosion behaviors of steel bars in a cement-based composite, and found that the corrosion rate exhibited a tendency to increase in mortar or paste specimens with the addition of CF or CNT, but showed a decrease in concrete specimens with the addition of CF or graphite powder [30–32].

In the few previous investigations, the relationships between electrical conductivity and corrosion behavior were not explored, and the corrosion mechanism of a steel bar in a cement-based conductive composite remains unclear. Therefore, in this paper, we aim to investigate the relationships between the electrical conductivity of cement-based conductive composites and the corrosion behavior of steel bars, providing a reference for the application of cement-based conductive composites as a type of functional and structural material.

2. Experimental details

2.1. Experimental preparation

Polyacrylonitrile- (PAN-) based CF produced by Shanghai Lishuo Composites Co., Ltd (China) was used, and its properties are shown in Table 1. Ordinary Portland cement (C, P.O. 42.5) produced by YaTai Group (China) was adopted, and its composition is given in Table 2. China ISO standard sand produced by Xiamen ISO Standard Sand Co., Ltd (China) was used to fabricate the test specimens. Methylcellulose (MC, mol wt. 40000–180000) produced by Tianjin Chemical Reagent Co., Ltd. (China) was used to disperse the CF. Polycarboxylate superplasticizer and tributyl phosphate were adopted as the water-reducing agent (WRA) and defoamer, respectively. Q235 carbon steel was chosen for the investigation of its corrosion behavior in a cement-based conductive composite, and its chemical composition is presented in Table 3.

Water/cement (w/c) and sand/cement (s/c) ratios were 0.5 and 2, respectively. The WRA was used in the amount of 1.0% by mass of cement, and the defoamer in the amount of 0.1% by mass of cement was added to reduce the bubbles introduced by the addition of CF. Specimens with the additions of 0–2.4 wt% CF versus the mass of cement were fabricated. First, the CF, dispersant, WRA and defoamer were added into water, and then the mixture was stirred for 1 min by hand. Afterwards, the mixture was dispersed for 60 min in an ultrasonic cleaner at 20 °C. Then, cement and sand were successively added into the mixture during the mixing process in a laboratory mortar mixer, and the mixture was again stirred for 3 min. A vibrator was used to vibrate the mortar specimen to make it denser. Three specimens of each type were prepared for testing.

2.2. Experimental procedures

To eliminate the effect of polarization on the measured results, the well-known four-electrode method was adopted to measure the electrical resistance of the specimens [9], as shown in Fig. 1. A specimen of size $40 \times 40 \times 50\ mm^3$ was prepared to test the electrical resistivity of the composite, and four stainless-steel meshes with openings measuring $3.35 \times 3.35\ mm^2$ were embedded into the specimen to be used as four electrodes. After 24 h under a sealing environment, all of the specimens were demolded, and then cured in a 20 °C, 100% relative humidity environment for 13 d. The specimens were dried for 18 h in a 50 °C oven before electrical conductivity testing. A standard resistor that approximates the resistance of the measured specimen was connected in series. The DC power outputted a small electrical current, and then the voltages of both ends of the standard resistor and the specimen were simultaneously collected by using an ADAM4117 card and AdamApax.NET Utility software [Advantech Co., Ltd (Taiwan)]. The current in the specimen was equal to that of the standard resistor, so the resistance of the specimen (R) was calculated by the following equation:

$$R = \frac{UR_0}{U_0}, \tag{1}$$

where U and U_0 are the measured voltages between the two ends of the specimen and the standard resistor, respectively; R_0 is the resistance of the standard resistor.

After the electrical conductivity of the CF-enhanced mortar was measured, some representative additions of CF in each conductive zone that were based on the test results of the electrical conductivity were chosen to fabricate the specimens used to investigate the corrosion behavior. The size of specimens was $40 \times 40 \times 140\ mm^3$, and a polished Q235 steel bar (Φ6 mm × 160 mm) was placed into the center of the specimen. After being demolded, both ends of each steel bar exposed outside the specimen were welded with conductive wire, and then were insulated by Teflon™ tape and glass cement. The preparation process and the curing conditions were the same as those for the specimens fabricated for the electrical resistivity testing. In order to shorten the testing period, an accelerated corrosion method is required. The common methods of accelerating the corrosion of RC structure include the impressed current electrochemical [33] and harsh artificial erosion environment techniques. The latter technique was more suitable for this research, and was carried out by using a dry-wet cycle experimental method. The specimens ($40 \times 40 \times 140\ mm^3$) were dried for 162 h in a 60-°C oven, and were then immersed into a 3.5-wt% NaCl solution for 6 h under room temperature [34]; this was a dry-wet cycle of 7 d. During each dry-wet cycle, because the mortar specimens were placed in the dry, high-temperature environment for a long time, a massive amount of chloride ions could easily penetrate to the surface of the steel bar once the specimens were immersed in the NaCl solution, which would strongly accelerate the corrosion of the steel bar. Accelerated corrosion testing ended when the corrosion-induced expansive force of the steel bar resulted in the appearance of cracks on the surface of the specimens.

The electrochemical technique based on polarization resistance (R_p) was used to analyze the corrosion behaviors of a steel bar in a conductive composite. The polarization resistance R_p is determined

Table 1
Properties of carbon fiber.

Diameter	Length	Purity	Surface	Conductivity
7 μm	3 mm	>93.0%	90–120 m^2/g	6.7×10^2 S/cm