Pergamon

Cement and Concrete Research, Vol. 28, No. 4, pp. 549–554, 1998

0008-8846/98 $19.00 + .00

PII S0008-8846(98)00011-8

STUDY ON THE HOLE CONDUCTION PHENOMENON IN CARBON FIBER-REINFORCED CONCRETE

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(Received June 10, 1997; in final form January 14, 1998)

ABSTRACT

The thermoelectric force (TEF) measurements on carbon fiber-reinforced concrete (CFRC) containing short PAN-based carbon fibers (0.2 ~ 1.2 wt.%) and plain concrete are conducted. TEF is observed in CFRC specimens but not in plain concrete specimens, and the cold end is the positive electrode of TEF while the warm end is the negative electrode. This phenomenon stems from the motion of positive hole in carbon fiber. Therefore, besides ion conduction and electronic conduction, hole conduction exists in CFRC, and hole conduction is the most important of the three. As a result, the conductivity of CFRC(σ) is made up of ionic conductivity (σ_i), hole conductivity (σ_h), and electronic conductivity (σ_e); that is, $\sigma = \sigma_i + \sigma_e + \sigma_h$. A new conduction model of CFRC is proposed at the end of the paper. © *1998 Elsevier Science Ltd*

Introduction

It is well known that concrete, as a type of widely used engineering material, is a kind of insulating material. Its structure, component, and mechanical properties have been greatly researched in recent years, but scientists pay little attention to its electrical properties (1). Concrete containing carbon fiber can improve its mechanical properties (2) and conductive properties (3), so it has important applications in the electrical and electronic, military, and construction industries; for example, it can provide electromagnetic interference shielding (4), cathodic protection of reinforcing steel in concrete structures (5), and can act as a resistor. Recent studies about carbon fiber-reinforced concrete (CFRC) show that it can be used as an intrinsically smart structure material that is capable of non-destructive flaw detection. This capability, which is critically needed for water dams, bridges, and nuclear power plants, is based on the notion that the volume electrical resistivity of CFRC changes with compressive stresses (6–8).

In the field of CFRC conduction mechanics, there are two basic types of electrical conduction: electronic conduction and ionic conduction (3,9). The former is through the

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TABLE 1
The properties of carbon fiber.

Item	Diameter /μm	Tensile strength /GPa	Tensile modulus /GPa	Resistivity /Ω·m	Density /g·cm^{-3}
Target	7 ± 0.2	≥1.95	≥175	25.0×10^{-5}	≥1.75

motion of free electrons in carbon fiber, and the latter is through the motion of ions (Ca^{2+}, Na^{+}, K^{+}, OH^{-}, SO_4^{2-}, etc.) in the pore solution (9).

In this paper, the thermoelectric force (TEF) measurements on CFRC containing short PAN-based carbon fibers (0.2 ∼ 1.2 wt.%) and plain concrete are conducted. We have discovered the hole conduction phenomenon through experiments.

Experiment Procedure

Materials and Specimens

The short carbon fibers (Shanghai Carbon LTD. CO.) were derived from polyacrylonitrile (PAN) precursor treated at a heat treatment temperature (HTT) of 1000°C. The nominal fiber length was 5 mm. The fiber properties are shown in Table 1. The matrix was Portland cement (525#); the disperser, which was a compound of cellulose and chloroform, was added to disperse the fibers.

The specimens were made according to Table 2. Water, carbon fiber, and the disperser were mixed by hand for about 2 min., then this mixture and cement were mixed in the mixer for 2 min. After pouring the mix into oiled molds ($4 \times 4 \times 4$ cm^3), a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day, then allowed to cure at room temperature in air for 28 days. Finally, graphite conductive paste was used to bond the copper wires to specimens.

TABLE 2
Mix proportions of the specimens.

Number	Fiber (wt. %)	Water/Cement ratio (%)	Disperser/Cement (%)
1	0.2	0.3	0.2
2	0.4	0.3	0.4
3	0.6	0.3	0.5
4	0.8	0.3	0.6
5	1.0	0.3	0.8
6	1.2	0.3	1.0
7	0.0	0.3	0.2

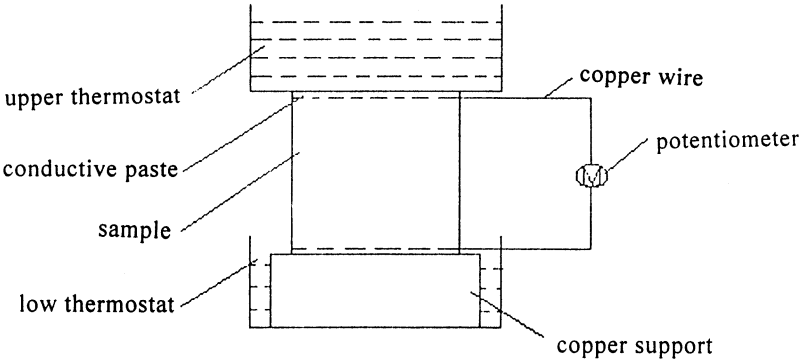

FIG. 1.
The experimental setup.

Experiment Setup

A UJ36 potentiometer was used to measure thermoelectric force (TEF). The temperature differential was obtained by means of the upper thermostat and the low thermostat. The experimental setup is illustrated in Figure 1. The ambient temperature during measurement was 25°C.

Results and Discussion

TEF values vs. temperature differential (Δt) with different concentration of carbon fiber are plotted in Figure 2. As shown in Figure 2, TEF is confirmed to be proportional to Δt. It is interesting to note that the cold end of the specimen is the positive electrode of TEF, the warm end is the negative electrode. In addition, TEF is not found in plain concrete specimens.

The relationship between TEF and Δt for a bundle of carbon fibers which contains 1,000 filaments is shown in Figure 3. The same phenomena as CFRC are observed, and the size of TEF in continuous carbon fiber lies between that occurring in CFRC containing 0.4 wt.%

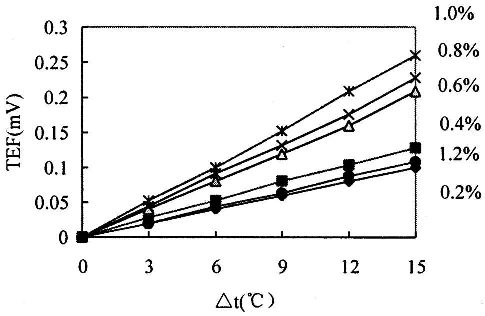

FIG. 2.
The relationship betweent and TEF of CFRC.

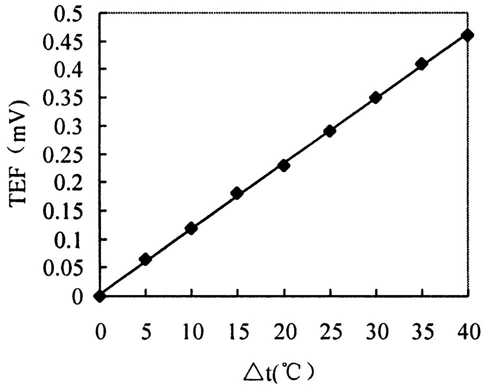

FIG. 3.
The relationship betweent and TEF of carbon fiber.

short carbon fiber and that in CFRC containing 0.6 wt.% short carbon fiber; therefore, TEF of CFRC only depends on the addition of carbon fiber to concrete.

When PAN-based precursor was treated to between 600°C to 1750°C, the carbonization process left a large excess of positive holes in the valence band (10). When the temperature differential is applied to the specimen, the temperature of one end is higher than the other. Consequently, the concentration of positive holes near the warm end is higher than the cold end; the difference in density leads to the spread motion of positive hole. The cold end is the positive electrode due to gaining positive hole, and the warm end is the negative electrode due to losing positive hole; therefore an electric field is formed between the cold end and the warm end. Under the electric field, positive hole may drift from the cold end to the warm end; when the spread motion balances with the drifting motion, steady TEF is formed.

The above analysis is consistent with the experimental results. This leads to the conclusion that, besides electronic conduction and ionic conduction, hole conduction exists in CFRC and is the most important among them. As a result, the conductivity of CFRC(σ) is made up of ionic conductivity (σ_i), hole conductivity (σ_h), and electronic conductivity (σ_e), that is:

$$\sigma = \sigma_i + \sigma_e + \sigma_h$$

$$\text{or} \quad \sigma = n_i q_i \mu_i + q(n_e \mu_e + n_h \mu_h)$$

In the experiment, because the carbon fiber content is low there are hardly any contacts among adjacent fibers (see Fig. 4a). In this condition, positive hole could be thermally excited and make a leap from one fiber to another; this phenomenon is called tunneling effect in quantum mechanics (1). With increasing fiber concentration, some fibers are in contact with each other, and hence form continuous fibers through the entire matrix. The positive hole can transport through the specimen not only by tunneling effect but also via these continuous fibers. As the ratio of carbon fiber continues increasing, the connectivity of fibers is improved and a conductive network is formed, so that the positive hole can transport along this conductive network (see Fig. 4b).

The above mentioned description can be illustrated by Figure 5b, c, and d, where the conduction model of CFRC is shown.

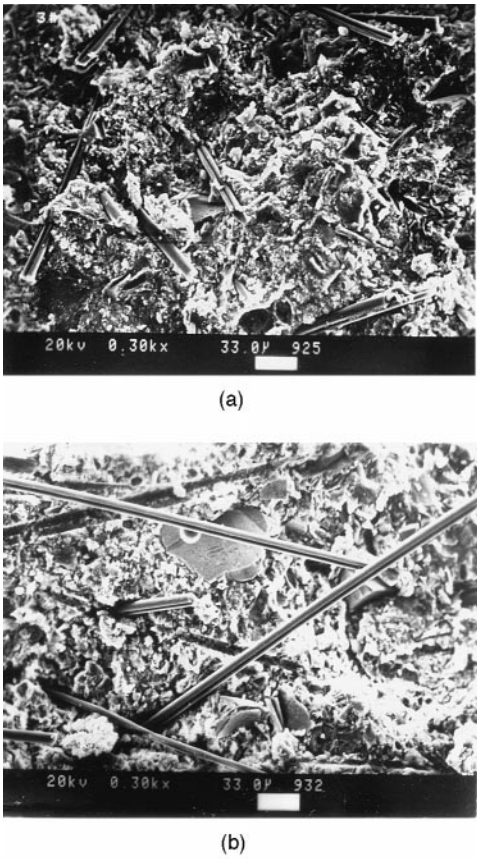

FIG. 4.
A) The content of carbon fiber is 0.2 wt.%. *B*) The content of carbon fiber is 0.8 wt.%

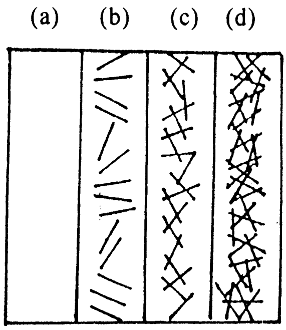

FIG. 5.
The conduction model of CFRC.

In this conduction model, the conduction of electric current through CFRC containing short carbon fibers can have four paths:

1. ionic conduction through the free evaporable water in paste;
2. electronic conduction and hole conduction through the fiber and paste in series;
3. electronic conduction and hole conduction through continuous fibers; and
4. electronic conduction and hole conduction through the conductive network of fibers.

As the carbon fiber content is low, current is mainly conducted through paths 1 and 2. With increasing fiber concentration, paths 2 and 3 are the principal ones. When the ratio of carbon fiber continues to increase, path 4 is the main one.

Conclusion

TEF is observed in CFRC specimens containing short PAN-based carbon fibers (0.2 ~ 1.2 wt.%), and the cold end is the positive electrode of TEF while the warm end is the negative electrode. This phenomenon stems from the motion of positive hole in carbon fiber. Therefore, besides ionic conduction and electronic conduction, hole conduction exists in CFRC, and hole conduction is the most important among them. The conductivity of CFRC(σ) is made up of ionic conductivity (σ_i), hole conductivity (σ_h), and electronic conductivity (σ_e), that is, $\sigma = \sigma_i + \sigma_e + \sigma_h$. As shown in the conduction model of CFRC, the conduction of electric current through CFRC containing short carbon fibers has four paths.

Acknowledgements

Financed by the National Science Foundation of China Key Project (59430261).

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