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THERMOELECTRIC PERCOLATION PHENOMENA IN CARBON FIBER-REINFORCED CONCRETE

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ABSTRACT

The measurements of thermoelectric power (TEP) and conductivity on carbon fiber-reinforced concrete (CFRC) containing short polyacrylonitrile-based carbon fibers (0.2–2.0 wt.%) were conducted. Percolation phenomena in CFRC associated with TEP were observed. TEP in CFRC increases, with the content of short carbon fiber increasing from 0.2 to 1.0 wt.%. As the content of carbon fiber reaches 1.2 wt.%, TEP decreases abruptly. In the end, TEP is almost maintained marginally with increasing content of carbon fiber from 1.4 to 2.0 wt.%. Therefore, the threshold is 1.2 wt.%, which is the same as the percolation content associated with conductivity. The results provide an important guide for the manufacture of smart concrete that has the ability for thermal self-diagnosis. *© 1998 Elsevier Science Ltd*

Introduction

Smart structures capable of nondestructive health monitoring in real time are of increasing importance because of the need to maintain the functions of critical civil infrastructure systems, such as bridges and dams. Carbon fiber-reinforced concrete (CFRC) is an intrinsically smart material that can sense compressive or tensile stress both in elastic and inelastic regimes. This capability is based on the notion that the volume resistance of CFRC changes with the outward stress; thus, it is a new sensor technology for in situ health monitoring of concrete structures. In this technology, concrete itself is the sensor, so there is no need to embed strain gages, optical fibers, or other sensors in the concrete, and it can allow the structural integrity of the host to be maintained (1–3).

Recent study shows that CFRC can sense temperature because of the Seebeck effect (4). In this paper, a good linear relationship is reported between thermoelectric force (TEF) and the temperature differential, and the thermoelectric power (TEP) of CFRC is about one third to one half that of the K-type metallic thermocouple. Taking advantage of this effect, CFRC can be used as the thermal sensor. Thermal load is very important in bulk concrete structures, such as dams, where the variation of temperature due to cement hydration and sun radiation may bring about tensile stress that can cause cracking of the concrete structure. Therefore, it is necessary to perform

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TABLE 1
Properties of carbon fiber.

Item	Diameter (μm)	Tensile strength (Gpa)	Tensile modulus (Gpa)	Resistivity (Ω.m)	Density (g.cm^{-3})
Target	7 ± 0.2	$\geqslant$1.95	$\geqslant$175	25.0×10^{-5}	$\geqslant$1.75

Six specimens of each fiber content are made according to Table 2 within which wt.% means % by weight of cement. Carbon fiber and disperser are mixed by hand for about 2 minutes, then this mixture and cement are mixed in a cement paste mixer for 2 minutes. After pouring the mix into oiled molds($4 \times 4 \times 4$ cm^3), a vibrator is used to decrease the amount of air bubbles. The specimens are demolded after 1 day then allowed to cure at room temperature in air for 28 days. Then two electrodes made by carbon cloth are stuck on the opposite surfaces of each specimens with graphite conductive paste(see Fig. 1), and graphite conductive paste is cured under certain temperature and pressure to ensure the excellent contact between the electrode and specimen. These two electrodes are used to measure TEF and electrical resistance(5).

internal thermal self-monitoring to diagnose the safety of dams. Study of the thermal self-monitoring property of CFRC is just as important as that of stress self-diagnosis.

In this paper, measurements of TEP and conductivity on CFRC containing short polyacrylonitrile (PAN)-based carbon fibers (0.2–2.0 wt.%) were conducted. Percolation phenomena associated with TEP were observed throughout the experiments.

Experiment Procedure

Materials and specimens

The short carbon fibers (Shanghai Carbon Ltd. Co.) are derived from PAN precursor treated at a heat treatment temperature of 1000°C. The nominal fiber length is 5 mm. The fiber

TABLE 2
Mix proportions of the specimens.

No.	Fiber (wt.%)	Water/cement ratio (%)	Disperser/cement (%)
1	0.2	30	0.2
2	0.4	30	0.4
3	0.6	30	0.5
4	0.8	30	0.6
5	1.0	30	0.8
6	1.2	30	1.0
7	1.4	30	1.2
8	1.6	30	1.4
9	1.8	30	1.6
10	2.0	30	1.8

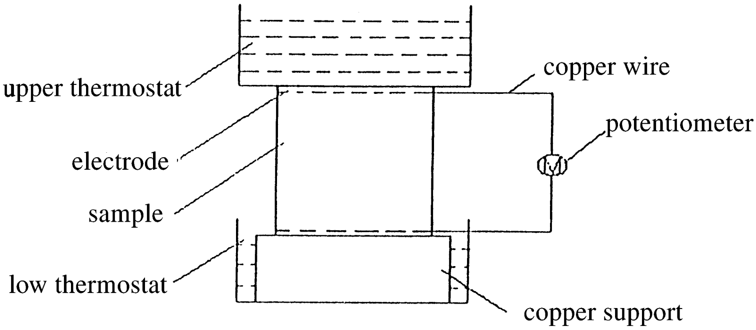

FIG. 1.
Experimental set-up.

properties are listed in Table 1. The matrix is Portland cement (no. 525); the disperser, which is a compound composed of cellulose and chloroform, is added to disperse the fibers.

Six specimens of each fiber content are made according to Table 2, where wt.% indicates percent by weight of cement. Carbon fiber and disperser are mixed by hand for about 2 min, then this mixture and cement are mixed in a cement paste mixer for 2 min. After pouring the mix into oiled molds ($4 \times 4 \times 4$ cm^3), a vibrator is used to decrease the amount of air bubbles. The specimens are demolded after 1 day and allowed to cure at room temperature in air for 28 days. Two electrodes made of carbon cloth are adhered to opposite surfaces of each specimen using graphite conductive paste (Fig. 1), which is cured under specific temperature and pressure to ensure excellent contact between the electrode and specimen. These two electrodes are used to measure TEF and electrical resistance (5).

Experimental set-up

The experimental set-up is illustrated in Figure 1. The temperature differential is gained by means of the upper thermostat and the low thermostat. The UJ36 potentiometer is used to measure TEF. The ambient temperature during the experiment was 25°C.

The DT9203 multimeter is used to measure electrical resistance, and conductivity is calculated according to the following equation:

$$\sigma = \frac{L}{R \cdot S}.$$

Results and Discussion

TEP values vs. the concentration of carbon fiber is plotted in Figure 2. As shown in Figure 2, TEP in CFRC increases, with the content of short carbon fiber changing from 0.2 to 1.0 wt.%. As the content of carbon fiber reaches 1.2 wt.%, TEP decreases abruptly, then almost maintains marginally in the range from 1.4 to 2.0 wt.%. It seems that TEP values vs. the

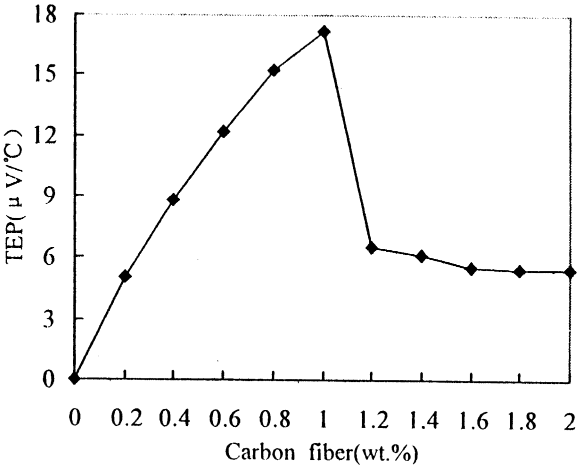

FIG. 2.
Relationship between the content of carbon fiber and TEP.

concentration of carbon fiber curves have features typical of percolation phenomena. This is characterized as follows.

1. TEP decreases three times, when the concentration of carbon fiber reaches a critical value of 1.2 wt.%, referred to as the threshold.
2. TEP is maintained marginally with increasing content of carbon fiber in the post-threshold region.

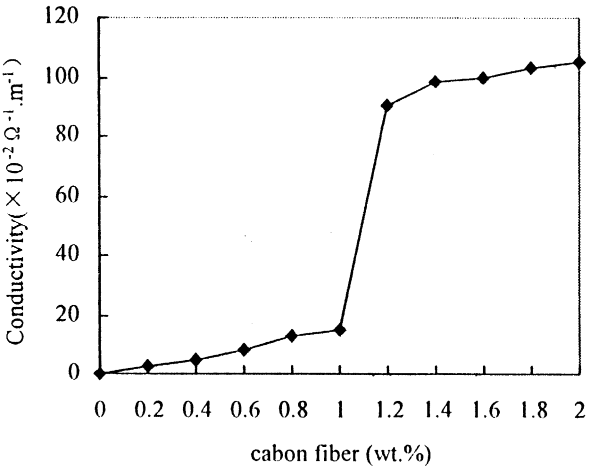

FIG. 3.
Relationship between the content of carbon fiber and conductivity.

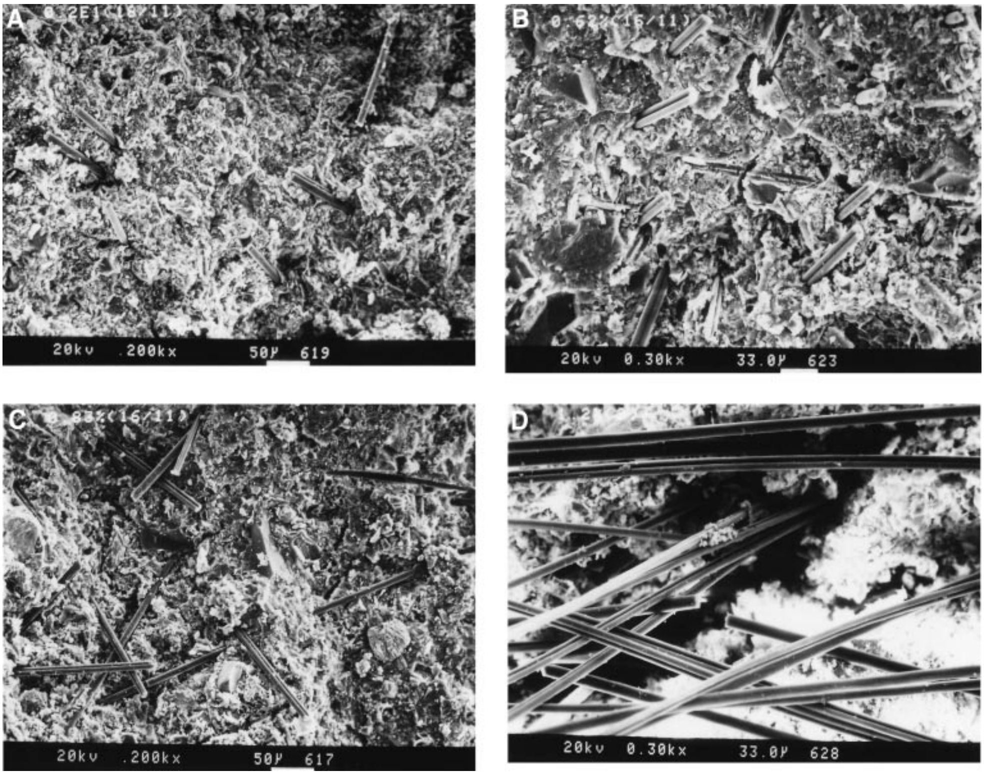

FIG. 4.
Content of fiber is *(A)* 0.2 wt.%, *(B)* 0.6 wt.%, *(C)* 0.8 wt.%, and *(D)* 1.2 wt.%.

Conductivity values vs. the concentration of carbon fiber is plotted in Figure 3. As shown in Figure 3, percolation phenomena associated with conductivity can be seen. The same phenomena has been reported (6,7).

In contrast with Figures 2 and 3, it is obvious that percolation thresholds are both 1.2 wt.%.

The Seebeck effect of CFRC is related to the motion of positive holes in carbon fibers through the cement matrix and fibers (4,8). When temperature differential is applied to the specimen, the concentration of the positive hole near the warm end is higher than at the cold end, so the diffusion motion of the positive hole takes place due to the concentration gradient. The cold end is the positive electrode due to gaining positive hole; 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, the positive hole may drift from the cold end to the warm end. When the diffusion motion balances with the drift motion, steady TEF is formed.

In the region of low fiber concentration, the fiber is distributed homogeneously in the nonconductive matrix, and the positive hole can transport through the tunneling effect (Figs. 4A and 4B) (7). With increasing fiber concentration, some fibers are in contact with each other, forming continuous fibers through the entire specimen (Fig. 4C). As the ratio of carbon fiber continues to increase, the conductive network is formed (Fig. 4D). On this basis, although the connectivity of fibers is improved with increasing fiber concentration, conductivity hardly changes because the conductive network is already formed. At last, the electrical percolation phenomenon appears.

From this analysis, the connectivity of fibers is improved in the range from 0.2 to 1.0 wt.%. Because it is beneficial to the transport process of the positive hole in cement paste, TEP increases. When the fiber content reaches 1.2 wt.%, the conductive network is formed, and the diffluence of positive hole through randomly distributed fibers appears. Therefore, the quantity of positive hole that can reach the cold end of the specimen decreases, and TEP decreases abruptly. In the range of 1.4 to 2.0 wt.%, because the conductive network is already formed, the influence of the diffluence does not increase obviously; thus, TEP is maintained marginally.

Conclusion

Percolation phenomena in CFRC associated with TEP is observed. TEP in CFRC increases, with the content of short carbon fiber increasing from 0.2 to 1.0 wt.%. As the content of carbon fiber reaches 1.2 wt.%, TEP decreases abruptly. In the end, TEP is almost maintained marginally, with increasing content of carbon fiber from 1.4 to 2.0 wt.%. Therefore, the threshold is 1.2 wt.%, which is the same as the percolation content associated with conductivity.

References

1. P.-W. Chen, D.D.L.Chung, Smart Mater. Struct. 2, 22 (1993).
2. P.-W. Chen, D.D.L.Chung, J. Am. Ceram. Soc. 78, 816 (1995).
3. Q. Mao, B. Zhao, D. Sheng, Z. Li, J. Wuhan Univ. Tech. 11, 41 (1996).
4. M. Sun, Z. Li, D. Sheng, Chin. J. Mater. Res. (Cailiao Yanjiu Xuebao). 12, 111 (1998).
5. B. Zhao, Z. Li, D. Wu, J. Wuhan Univ. Tech. 10, 30 (1995).
6. P. Xie, P. Gu, J.J.Beaudoin, J. Mater. Sci. 31, 4093 (1996).
7. Z. Shui, J. Li, F. Huang, D. Yan, J. Wuhan Univ. Tech. 10, 37 (1995).
8. M. Sun, Z. Li, Q. Mao, D. Shen, Cem. Concr. Res. 28, 549 (1998).