Pergamon

Cement and Concrete Research 30 (2000) 1593–1595

CEMENT AND CONCRETE RESEARCH

A study of piezoelectric properties of carbon fiber reinforced concrete and plain cement paste during dynamic loading

Mingqing Sun[a,*], Qingping Liu[a], Zhuoqiu Li[a], Yaozu Hu[b]

[a]State Key Laboratory of Materials Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, People's Republic of China
[b]Department of Mathematics and Physics, Wuhan University of Technology, Wuhan 430070, People's Republic of China

Received 3 January 2000; accepted 13 June 2000

Abstract

Carbon fiber reinforced concrete (CFRC) is an intrinsically smart material, which can be used to realize the self-monitoring of concrete structures based on its piezoresistance effect and the Seebeck effect. An experimental study was made to examine the piezoelectric properties of CFRC and plain cement paste. The results show that both CFRC and plain cement paste exhibit piezoelectric behavior, which can be explained in terms of a solid–liquid interface double-layer model. Furthermore, they can sense a large range of loading rates with high sensitivity. The materials are good sensors for monitoring the dynamic loading. Therefore, a new method to make smart concrete structures can be developed.

Keywords: Fiber reinforced; Concrete; Composite; Electrical properties

1. Introduction

Smart structures capable of nondestructive performance monitoring in real time are of increasing importance due to the need to maintain the functions of critical civil infrastructure systems, such as bridges and dams. Carbon fiber reinforced concrete (CFRC, containing fiber in amounts as small as 0.2 vol.%) is an intrinsically smart material that can sense compressive or tensile stress both in the elastic and inelastic regimes. This capability is based on the notion that the volume resistance of CFRC changes with applied stress. In addition, we have also discovered that CFRC exhibits Seebeck effect indicating that CFRC can sense the temperature of concrete. Thus, these are the bases for a new sensor technology for in situ performance monitoring of concrete structures. In this technology, concrete itself is the sensor. There is no need to embed strain gages, optical fibers, or other sensors in the concrete [1–5].

However, there are many problems to resolve before CFRC can be applied as a stress, strain or temperature sensor. The first relates to improving the resistance stability and the repeatability of CFRC. The second is how to separate the temperature influence on the electrical resistance of CFRC from the force influence. An additional challenge is to ensure good interface bond strength of CFRC with ordinary concrete structures, such as dams. In this paper, results demonstrating the piezoelectric effect of CFRC and plain cement paste are presented. This study provides information relevant to smart concrete structure technology.

2. Experiment

2.1. Materials and specimens

The short carbon fibers (Shanghai Carbon Ltd. Co.) are 5 mm in length. The fiber properties are given in Table 1. The matrix was Portland cement-based (525#). The compound of cellulose and chloroform were added to disperse the fibers. The mix proportion is provided in Table 2. Water, carbon fiber, and dispersing agent 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 (4×4×4 cm), a vibrator was used to decrease the amount of air bubbles. Before vibration, two electrodes made of carbon

* Corresponding author. Tel.: +86-027-87651970.
E-mail address: sunmingqing@163.net (M. Sun).

0008-8846/00/$ – see front matter
PII: S0008-8846(00)00338-0

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

Table 2
Mix proportions of the specimens

Fiber/cement (wt.%)	0.5
Water/cement (%)	30.0
Dispersing agent/cement (%)	0.4

fiber cloth were embedded in the paste in parallel. The specimens were demolded after 1 day, then allowed to cure at room temperature in air for 28 days.

The specimens of plain cement paste were made using similar methods. Only Portland cement (525#) and water were used.

Six specimens were made from each mix.

2.2. Testing procedure

A DT9203 multimeter was used to measure the voltage generated by the CFRC (resolution 0.01 mV). The UJ36 potentiometer (resolution 0.01 mV) was used for the voltage measurement of the plain cement paste because it has higher resistivity than CFRC. The experimental loading device was an MTS system. The direction of the loading and electrodes are shown in Fig. 1. The maximum load in our experiments is 8 kN, that is, about 1/4 to 1/3 of the compressive strength of the materials.

3. Results and discussion

(1) The piezoelectric smart behavior of CFRC is shown in Fig. 2. The loading sequence was: loading–unloading. The loading rate was 0.5 kN/s. As shown in Fig. 2, at the beginning of loading, the voltage increases quickly to a plateau, then remains relatively constant. During unloading, the voltage decreases at first, remains approximately constant until 4 kN and finally increases rapidly. When the load reaches zero, the voltage reaches zero.

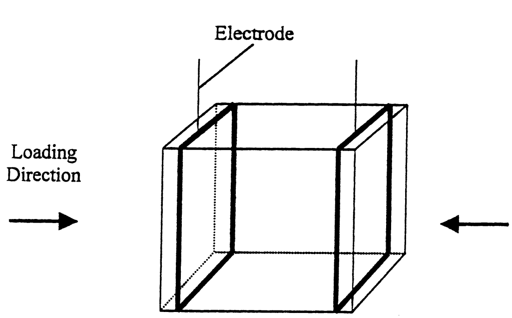

Fig. 1. Direction of the loading and electrodes.

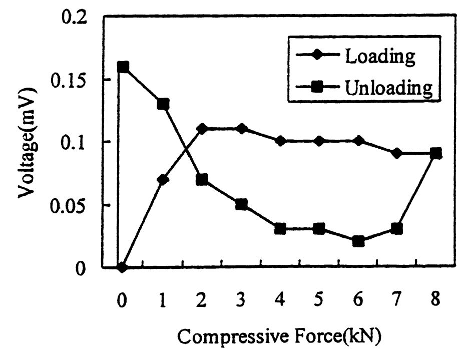

Fig. 2. Compressive force vs. voltage generated by the CFRC.

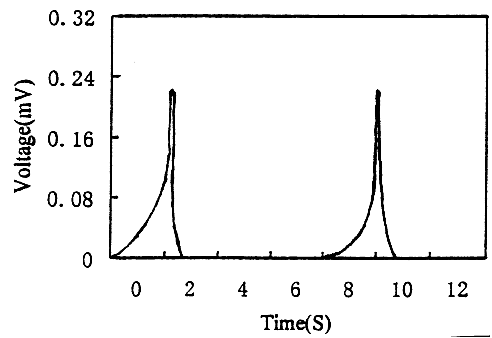

Fig. 3. Time vs. voltage generated by the CFRC (4 kN/s).

This phenomenon can be explained in terms of a solid–liquid interface double-layer model. Hydrated cement paste is frequently viewed as an insulating porous matrix. Its pores are filled with a conductive electrolyte. The main hydration product is C–S–H. It is emphasized that in any solid–electrolyte system there is a specific liquid region in contact with the solid surface, referred to as the double layer or diffuse layer. Ions in solution, such as Ca^{2+}, Na^{+}, K^{+}, OH^{-}, and SO_4^{2-} absorb on the solid surface. Similarly, the opposite charges line up on the solid side. Many scholars have used the double-layer theory to explain the formation and development of cement microstructure, the AC impedance spectra of cement paste [6–9]. In our

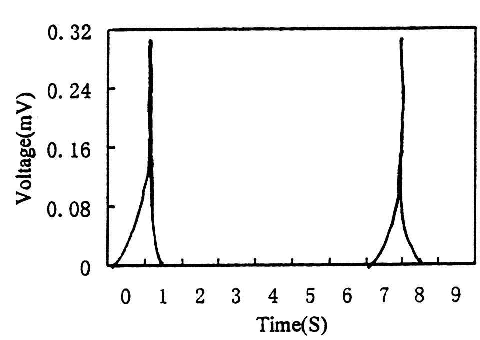

Fig. 4. Time vs. voltage generated by the CFRC (8 kN/s).

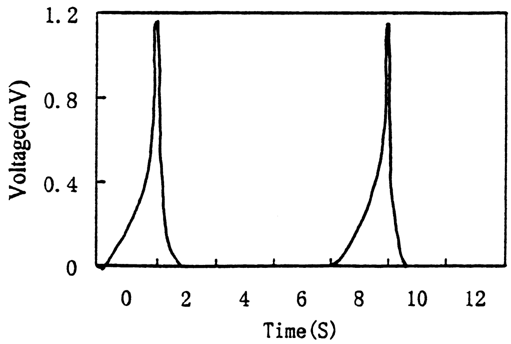

Fig. 5. Time vs. voltage generated by the plain cement paste (4 kN/s).

experiments, the electrode–cement system interface double layer also exists [7].

When the compressive force is applied, the interface shear stress causes the ions in the double layers to transport into the solution in the cement paste. Charges accumulate on the surface of electrode. As a result, a streaming potential difference occurs. Two phenomena are operative during loading: (a) the transportation of ions causes the potential difference, (b) the leakage of charges through the conductive paths of the CFRC leads to a decrease of the potential difference [8]. At the start, the increase in voltage is mainly due to (a). The stable state is the balance between (a) and (b). During unloading, part of the solution flows back (c) and another part of the solution refills the vacated pores (d). The descent of voltage is mainly due to (c). The stable state reflects a balance between (c) and (d). With the compressive force decreasing, the percentage of pores vacated increases, so (d) results in a voltage increase.

(2) Under a high loading rate, for example, 4 and 8 kN/S, each of the voltage–time relationships has two sharp peaks (Figs. 3 and 4). The loading sequence was: loading–sustaining (6 s)–unloading. These two peaks correspond with the voltage response increase during loading and unloading in Fig. 2. In the constant loading segment no voltage outputs, indicating no charge accumulation occurs. In contrast with Figs. 2–4, the sensitivity increases with the loading rate increasing. When the loading rate increases, the speed of ion transport increases, while the leakage of charge is relatively slow. Thus, the voltage can reach a larger value. Because CFRC can sense a large range of loading rate with high sensitivity, CFRC is thus a good sensor for monitoring the dynamic load.

(3) Fig. 5 shows that plain cement paste specimens also exhibit a piezoelectric effect. Thus, carbon fiber in cement composite materials is not directly responsible for the piezoelectric effect, while the special microstructure of hydrated cement paste which has been described in Section (1) is responsible for it. From Fig. 4, it is inferred that the plain cement paste is more sensitive than CFRC. Since the addition of carbon fiber improves the conductivity greatly, the leakage of charges in CFRC is faster than that in plain cement paste. Experiments have also been conducted using different loading rates; the results are similar to those of CFRC. Therefore, we can use concrete directly to perform self-diagnosis concrete structure.

4. Conclusions

(1) CFRC and plain cement paste exhibit piezoelectric characteristics, which is due to the transportation of ions in the double layer under compressive stress.

(2) CFRC and plain cement paste are sensitive to a large range of loading rates. They are good sensors for monitoring the dynamic load.

(3) The plain cement paste is more sensitive than CFRC. Therefore, we can use concrete directly to perform self-diagnosis of a concrete structure.

(4) The study on the piezoelectric effect of CFRC and cement paste provide the basis for the development of a new method for producing smart concrete structures.

Acknowledgments

We appreciate the help of The Physics Laboratory of Wuhan University of Technology.

References

[1] P.-W. Chen, D.D.L. Chung, Carbon fiber reinforced concrete for smart structures capable of non-destructive flow detection, Smart Mater Struct 2 (1993) 22–30.
[2] S. Wang, X. Shui, X. Fu, D.D.L. Chung, Early fatigue damage in carbon-fibre composites observed by electrical resistance measurement, J Mater Sci 33 (1998) 3875–3884.
[3] M. Sun, Z. Li, D. Shen, Seebeck effect of carbon fiber-cement based composite, Chin J Mater Res 12 (1) (1998) 111–112.
[4] M. Sun, Z. Li, Q. Mao, D. Shen, Study on the hole conduction phenomena in carbon fiber reinforced concrete, Cem Concr Res 28 (4) (1998) 549–554.
[5] M. Sun, Z. Li, Q. Mao, D. Shen, Study on thermal self-monitoring of carbon fiber reinforced concrete, Cem Concr Res 29 (5) (1999) 769–771.
[6] S. Chatterji, M. Kawamura, Electrical double layer, ion transport and reactions in hardened cement paste, Cem Concr Res 22 (1992) 774–782.
[7] P. Gu, P. Xie, J.J. Beaudoin, R. Brousseau, A.C. impedance spectroscopy: I. A new equivalent circuit model for hydrated portland cement paste, Cem Concr Res 22 (1992) 833–840.
[8] P. Gu, P. Xie, J.J. Beaudoin, R. Brousseau, A.C. impedance spectroscopy: II. Microstructural characterization of hydrating cement–silica fume system, Cem Concr Res 23 (1993) 157–168.
[9] P. Xie, P. Gu, Z. Xu, J.J. Beaudoin, A rationalized A.C. impedance model for microstructural characterization of hydrating cement paste, Cem Concr Res 23 (1993) 359–367.