Mechanism of Functional Responses to Loading of Carbon Fiber Reinforced Cement-based Composites

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Abstract: Single fiber pull-out testing was conducted to study the origin of the functional responses to loading of carbon fiber reinforced cement-based composites. The variation of electrical resistance with the bonding force on the fiber-matrix interface was measured. Single fiber electromechanical testing was also conducted by measuring the electrical resistance under static tension. Comparison of the results shows that the resistance increasing during single fiber pull-out is mainly due to the changes at the interface. The conduction mechanism of the composite can be explained by the tunneling model. The interfacial stress causes the deformation of interfacial structure and the interfacial debonding, which have influences on the tunneling effect and result in the change of resistance.

Key words: carbon fiber; functional response; tunneling effect; single pull-out; cement

1 Introduction

Carbon fiber reinforced cement-based composites is an intrinsically smart material that can sense elastic and inelastic deformation, as well as damage[1,2]. The sensing function refers to the ability to provide an electrical response to loading in real time. Researchers have paid attentions to applying this intrinsically smart material to non-destructive health monitoring in critical civil infrastructure systems.

It is important to understand the origin of the functional responses to loading of carbon fiber reinforced cement-based composites. It has been reported by Fu Xuli and Chung D D L[3] that the origin of this electromechanical effect was attributed to the slight fiber pull-out and the resulting increase in the contact electrical resistivity between the fiber and the matrix. They considered that this contact resistivity increases in turn resulted in an increase in the volume electrical resistivity of the composite.

In the composites, consisting of aggregates of electrons dispersed in the insulating matrix, the electrical conductivity can be ascribed to a mechanism of tunneling with potential-barrier modulation by thermal fluctuations[4-6]. It is evident that the smart properties of the carbon fiber reinforced cement-based composites are related to the electrical conductivity of the material. The deformation of the interfacial structure in the composites causes the change of electrical conductivity. In order to understand the origin of the functional response to load in carbon fiber cement-based composites, this paper made some investigation of the electromechanical behavior of the single fiber pull-out, as well as that of the carbon fiber itself.

2 Experimental

2.1 Methods

The cement used in the matrix was Portland cement with poor conductivity. The electrical resistivity of this material was the grade of 10^9 Ω•cm. In order to investigate the variation of electrical resistivity during single fiber pull-out, the conductive carbon black was used in the composites. The addition of carbon black (1.1 wt% of the cement) to the cement paste significantly decreased the resistivity to the grade of 10^3 Ω•cm.

Raw materials: Portland cement with grade of 42.5, PAN carbon fibers (the properties are shown in Table 1), conductive carbon black YT-1P, disperser CH-12B (provided by Shanghai Sanzheng Polymer Material Co., Ltd.).

2.2 Preparation of specimen

The single carbon fiber was disparted from a bundle under light microscope. The carbon fibers as
received have been surface treated at room temperature for 24 h in H₂O₂ (30% reagent). The length of the fiber prepared for the experiment was 55 mm.

Cement, carbon black, disperser, water were prepared in a proportion of 100:1.1:2.2:30. Firstly the disperser was added into water and stirred. Then the carbon black and cement were mixed with them. After being stirred for 3 min, the mixture was poured into the moulds. One end of the single fiber was embedded in the mixture (the embedment length L is about 2 mm), then the specimen was formed. Demouldation was taken after 1 d and then the specimen was cured at room temperature in air for 20 d.

### 2.3 Determination

The matrix and the other end of the fiber were attached vertically by adhesive to a piece of paper with a rhombus hole cut in it (Fig.1). The resistance was measured by four-probe method, using silver paint for the electrical contacts. The two outer contacts were used for current passing; the two inner contacts were made for voltage measurement. A current contact and a voltage contact were set on the matrix, while the other voltage and current contacts were on the fiber. Prior to vertical tension application, the sample was cut horizontally along the diagonal of the rhombus, under load control tension, with the loading speed of 0.2 mm/min.

### 3 Results and Discussion

Fig.2 shows the variation of the interfacial bonding force (i.e., the pull) with displacement during single fiber pull-out testing. Fig.3 shows the relationship between the fractional increase in resistance (ΔR/ΔR₀) and displacement. Where ΔR=R−R₀, R₀ is the resistance prior to pull-out testing. The interfacial bonding force and ΔR/ΔR₀ increased linearly with increase of displacement. The bonding force reached its maximum when the displacement was 0.361 mm, and simultaneously the ΔR/ΔR₀ abruptly increased, i.e., when the fiber-matrix debonding was completed. ΔR/ΔR₀ increased with increase of bonding force before this abrupt increase. The origin of this dependence is attributed to the deformation of interfacial structure between fiber and matrix.

### Table 1 Properties of carbon fibers

<table>
<thead>
<tr>
<th>Filament diameter (μm)</th>
<th>Tensile strength (GPa)</th>
<th>Tensile modulus (GPa)</th>
<th>Elongation at break (%)</th>
<th>Electrical resistivity (Ω•cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>4.0</td>
<td>240</td>
<td>1.4</td>
<td>25×10⁻⁵</td>
</tr>
</tbody>
</table>

Equipments: INSTRON 5848 MicroTester; Keithley 2700 Multimeter/data acquisition system.

The conduction mechanism of the composite can be explained by the tunneling effect[7], i.e., electrons move through the network, which formed by the conductive material and connect the insulation parts of the network by tunnel effect. The variation of the interfacial shear stress is expected to cause the deformation of the interfacial structure and the interfacial debonding, which can produce an influence.