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Electrical conductivity of self-monitoring CFRC

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Abstract

The present work is concerned with the analysis of the electrical conductivity in carbon fiber reinforced cement composites and of the main parameters influencing the phenomenon: fiber volume fraction, fiber length, hydration time and sand–cement ratio. AC measurements were carried out on CFRC (carbon fiber reinforced cement) and the experimental results were analyzed using the percolation theory. The present study could be useful for the adoption of CFRC as a smart material.

Keywords: Carbon fiber; Cement composites; Electrical resistivity; Percolation theory

1. Introduction

The main goal of much research in recent years, in the monitoring field, has been the development of "health monitoring systems", which generally involve the extensive use of sensors, embedded in structures during the production process, or externally bonded in critical positions.

A valid alternative to the use of sensors is the adoption of fiber-reinforced materials with a small percentage of conductive fibers, commonly called "self-monitoring" materials [1,2].

Previous studies [3,4] demonstrated that moist concrete has a resistivity of about $10^4\,\Omega$cm and this increases up to $10^{11}\,\Omega$cm for oven-dried concrete (105 °C). The plain concrete is an insulating material. The addition of fiber improves the mechanical performance and strongly modifies the electrical conductivity so producing a "self-monitoring" capability which is derived from the correlation of the damage level to the electrical behavior. Therefore the material itself becomes a sensor, is durable and allows the entire structure to be checked.

In this work, attention is focused on CFRC (carbon fiber reinforced cement composites), with the goal of characterizing the material from the electrical point of view. This is a prerequisite for successive developments which will allow the damage evolution to be evaluated by simple electrical measurement ERM (electrical resistivity monitoring).

In this initial research the principal objective is the evaluation of electrical conductivity phenomena, their modeling and the definition of the main parameters which affect the mechanical and electrical behavior, such as the effect of matrix microstructure, percentage of fibers, relative humidity, etc. The percolation theory is adopted to try to analytically model the observed phenomena because its statistical–mathematical nature appears capable of treating the multiphase system under analysis.

2. Experimental procedure

2.1. Materials and specimens

To make the mortar specimens, Portland cement (type I, 52.5 R) and standard sand, as prescribed by the UNI EN 196-1 (1996), were used. The geometrical

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and mechanical properties of the carbon fibers (PAN type) used in this analysis are listed in the following Tables 1 and 2.

To obtain a better fiber dispersion and mortar compactness, silica fume (15% by weight) was used. To recover the loss of workability produced by the silica fume a fluidifying agent was added. The specimens were made from a mix with the following ratios: water–cement ratio (w/c) = 0.45; sand–cement ratio (s/c) = 1; silica fume by 15% weight of cement; fluidifying-cement weight ratio = 0.4%. A standard mixing procedure was used. The fluid mortar was put into plexiglass moulds and was compacted using a shaking table. The specimens had the dimensions of 40 × 40 × 160 mm and were cured at constant temperature at 20 °C for 24 h. The tests were made in the laboratory atmosphere (temperature: +20 ± 2 °C; relative humidity: 65 ± 5%).

2.2. Electrical measurements

The electrical conductivity of the carbon fiber cement composites is fundamentally of two types: electrolytic and electronic. The first involves the matrix because it is connected to the ionic movement in the evaporable water of the cement composite [3].

The second one is connected with the movement of the free electrons present in the conductive phase, which are, in our case, the carbon fibers. In the present work a prevalence of the electronic part in the electrical conductivity is expected. Moreover, to eliminate the electrolytic effects, particularly the effect of the electrode polarization, an alternate current (AC) was adopted. In effect these polarization phenomena will not disappear but they can be modeled as resistance series or as a parallel capacitor.

For AC the Ohm law assumes the form $V = ZI$, where V, Z and I are phasors and they contain the information about the phase and the modulus (I is the current expressed in Ampere, V the potential in Volt and Z the impedance in Ohm). In the case of a parallel C–R arrangement, the impedance has the following expression:

$$Z = \frac{R}{(1 + \omega^2 C^2 R^2)^{1/2}}$$

$\omega = 2\pi f$, f is the frequency expressed in Hz, C is the capacity expressed in Faraday and R is the resistance expressed in Ohm.

The electrical measurements were conduced in a frequency range of 10–100 kHz and with a voltage of 10 mV. The frequency upper limit was chosen as a reference value for the electrical resistance, because at 100 kHz the practically constant value of the impedance indicates that it is close to its real part (pure Ohm resistance) [5,6].

The electrical resistance measurements were carried out using a Galvanostat/Potentiostat PARSTAT 2263-1 made by Princeton Applied Research (USA), with Power Suite acquisition processing data software (Fig. 1). The device has five electrodes: Ground (G), Working (W), Sense (S), Counter (C) and Reference (R) electrode. The two- and four-probe methods were used in the electrical measurements, as depicted in Fig. 2.

In the four-probe method, the current flows between C and W placed on external electrodes, while the potential is measured between R and S placed on the inner ones.

Fig. 1. Equipment used for electrical resistance measurements.

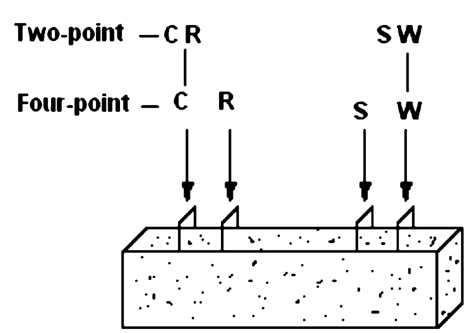

Fig. 2. Two- and four-probe electrical measurements: electrode set-up.

Table 1
Carbon fiber mechanical properties

Density (g/cm^3)	Tensile strength (GPa)	Young modulus (GPa)	Elongation at break (%)	Carbon content Wc (%)	Electrical resistivity (Ω cm)
1.75	2	180–240	1.20–1.30	>95	10^{-2}–10^{-3}

Table 2
Carbon fiber geometrical data

Diameter μ(m)	8	8	8
Length	4 μm	3 mm	6 mm