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CONTACT ELECTRICAL RESISTIVITY BETWEEN CEMENT AND CARBON FIBER: ITS DECREASE WITH INCREASING BOND STRENGTH AND ITS INCREASE DURING FIBER PULL-OUT

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ABSTRACT

The contact electrical resistivity between carbon fiber and cement paste was found to decrease with increasing bond strength and to increase during fiber pull-out from the paste. Both effects are due to the interfacial voids, which are electrically insulating. Evidence is provided in support of the feasibility for the volume electrical resistivity increase during tensile loading of carbon fiber reinforced cement to be due to fiber pull-out.

Introduction

The fiber-matrix bond strength has long been recognised as important for the mechanical properties of fibrous composite materials, including fiber reinforced concrete. It has been measured by single fiber pull-out testing [1]. Correlation of the bond strength with the fiber-cement contact electrical resistivity has recently been reported by the authors in the case of stainless steel fibers, for which the contact resistivity increases with increasing bond strength due to the presence of a high resistivity interfacial phase (probably a metal oxide) that helps the bonding [2]. This correlation has not been previously reported for the case of carbon fibers, which do not have an oxide film (other than a monolayer), in contrast to steel fibers. This correlation is not only scientifically interesting for the purpose of understanding the origin of the bonding, but it also provides a non-destructive method for assessing the bond strength. In contrast, the single fiber pull-out testing is a destructive method.

Concrete reinforced with short carbon fibers are attractive not only in its high flexural strength, high flexural toughness and low drying shrinkage [3-9], but also in its ability to serve as a strain sensor [10-12]. The strain sensing ability is associated with the change in the volume electrical resistivity of the concrete under static or dynamic loading. The origin of this electromechanical effect has been attributed to the slight fiber pull-out (slight opening of crack with a bridging fiber) and the resulting

Table 1 Properties of carbon fibers

Filament diameter	10 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	$3.0x10^{-3}$ Ωcm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt.%

increase in the contact electrical resistivity between the fiber and the matrix [11]. This contact resistivity increase in turn results in an increase in the volume electrical resistivity of the concrete. In order to provide quantitative support for this origin, this paper reports on the contact electrical resistivity between carbon fiber and cement, and furthermore investigates the variation of the contact resistivity during fiber pull-out.

The objectives of this paper are (i) to provide the correlation of the fiber-cement bond strength with the fiber-cement contact electrical resistivity in the case of carbon fibers, and (ii) to provide quantitative support for the feasibility for the notion that the strain sensing ability of carbon fiber reinforced concrete originates from the slight fiber pull-out and the resulting increase in the contact electrical resistivity.

Experimental Methods

The carbon fibers were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, Kentucky). The fiber properties are shown in Table 1. Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. The water reducing agent used in the amount of 0.5% by weight of cement was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93-96% sodium salt of a condensed naphthalenesulfonic acid. The volume electrical resistivity of the cement paste was 1.62×10^5 Ω.cm at 28 days of curing, as measured by the four-probe method using silver paint for electrical contacts.

The contact electrical resistivity between the fiber and the cement paste was measured at 28 days of curing using the four-probe method and silver paint as electrical contacts, as illustrated in Fig. 1. One current contact and one voltage contact were on the fiber, while the other voltage and current contacts were on the cement paste embedding the fiber to a distance ranging from 0.51 to 1.50 mm, as measured for each sample tested. The cement paste thickness was 1 mm on each side sandwiching the fiber. The fiber length was 1 cm. The current was 0.5-2.0 A; the voltage was 3-4 V. The resistance between the two voltage probes was measured; it corresponds to the sum of the fiber volume resistance, the interface contact resistance and the cement paste volume resistance. The measured resistance turned out to be dominated by the contact resistance, to the extent that the two volume resistance terms can be neglected. The contact resistivity (in Ω.cm^2) is given by the product of the contact resistance (in Ω) and the contact (interface) area (in cm^2), such that the contact area depends on the embedment length of the particular sample.

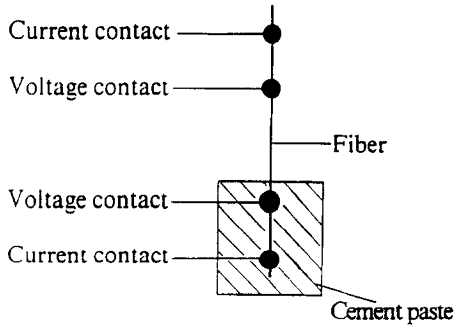

Fig. 1 Sample configuration for measuring the contact electrical resistivity of the interface between a fiber and cement paste.

Single fiber pull-out testing was conducted on the same interface samples and at the same time as the contact resistivity was measured. For pull-out testing, one end of the fiber was embedded in cement paste, as in Fig. 1. A Sintech 2/D screw-action mechanical testing system was used. The contact resistivity was taken as the value prior to pull-out testing. The bond strength was taken as the maximum shear stress during pull-out testing, such that the bond area depends on the embedment length of the particular sample. Nine interface samples were tested.

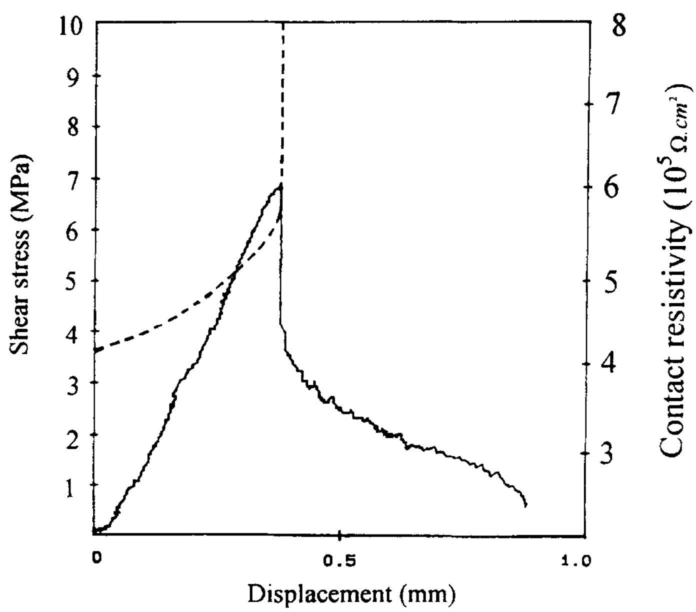

Fig. 2 Plots of shear stress vs. displacement (solid curve) and of contact electrical resistivity vs. displacement (dashed curve) simultaneously obtained during pull-out testing of carbon fiber from cement paste at 28 days of curing.

Table 2 Bond strength and contact electrical resistivity for the nine samples tested. The error ranges for bond strength and contact resistivity are consequences of that for the embedment length.

Embedment length (mm) ±0.02	Bond strength (MPa)	Contact resistivity (Ω.cm^2)
1.20	3.23 ± 0.05	$7.03 \times 10^5 \pm 1.2 \times 10^4$
0.51	4.76 ± 0.19	$6.53 \times 10^5 \pm 2.6 \times 10^4$
0.54	5.53 ± 0.21	$5.43 \times 10^5 \pm 2.0 \times 10^4$
1.40	5.61 ± 0.08	$5.30 \times 10^5 \pm 7.6 \times 10^3$
0.69	6.77 ± 0.20	$4.71 \times 10^5 \pm 1.4 \times 10^4$
0.51	6.89 ± 0.28	$4.65 \times 10^5 \pm 1.8 \times 10^4$
1.50	6.96 ± 0.09	$4.51 \times 10^5 \pm 6.0 \times 10^3$
1.50	7.35 ± 0.09	$3.62 \times 10^5 \pm 4.8 \times 10^3$
0.81	7.85 ± 0.20	$3.10 \times 10^5 \pm 7.7 \times 10^3$

Results

Fig. 2 gives a typical plot of shear stress vs. displacement and the simultaneously obtained plot of contact resistivity vs. displacement at 28 days of curing. The contact resistivity gradually increased prior to the abrupt increase when the shear stress had reached its maximum. The stress also gradually increased as debonding took place and reached its maximum when the fiber-matrix debonding was completed. In other words, the contact resistivity increased as debonding took place.

Table 2 gives the embedment length, bond strength and contact electrical resistivity of the nine samples tested at 28 days. Fig. 3 shows the correlation of the contact resistivity with the bond strength for the nine samples (identically prepared, though with various embedment lengths). The contact resistivity decreased with increasing bond strength. Three of the nine samples had essentially the same embedment length of 0.5 mm; another three samples had embedment lengths around 1.5 mm (Table 2). The same correlation was observed within each of these two groups of samples. This means that the correlation is not due to the variation in embedment length.

Discussion

For steel fibers, the contact electrical resistivity increases with increasing bond strength [2]. However, for carbon fibers, the contact resistivity decreases with increasing bond strength. This difference is attributed to the presence of an oxide film on steel and the absence of an oxide film (except for a monolayer) on carbon. The oxide film on steel helps the bonding, but its high volume electrical resistivity causes the contact resistivity to increase. For carbon fibers, poor bonding is associated with a large void content at the interface. The voids are electrically insulating, so they cause the contact resistivity to be high.

The bond strength obtained in this work for carbon fibers is higher than the value of 2 MPa previously reported [1], probably due to the difference in cement paste formulation. The average bond strength for the nine samples is 6.11 MPa. The variation among the nine samples is not due to the error

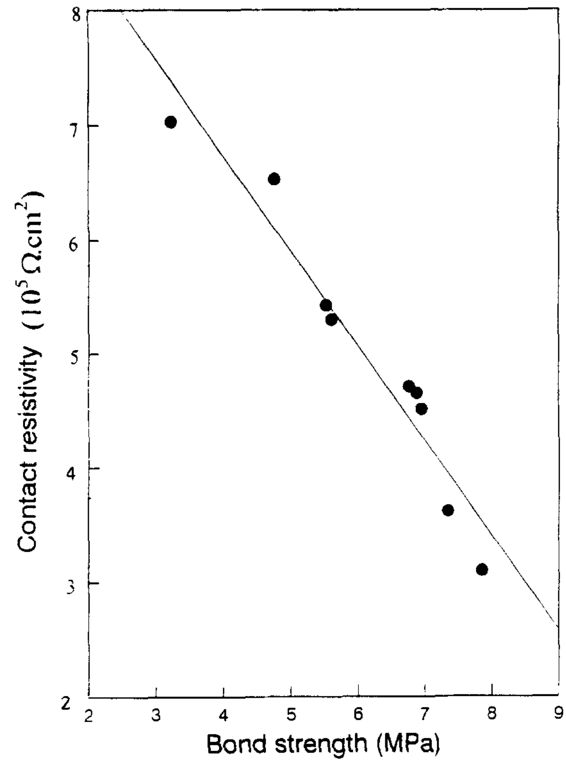

Fig. 3
Variation of contact electrical resistivity with bond strength at 28 days of curing.

in the experimental measurement, but reflects the true variation from sample to sample, since the bond strength correlates nicely with the contact resistivity among these nine samples.

Taking the bond strength as 6.11 MPa and assuming that all the fibers are oriented parallel to the tensile stress axis, we find by a simple calculation that uniformly distributed 5 mm-long fibers in the amount of 0.0082 vol.% require a tensile stress of 1 MPa for them to all debond. Ref. 10 reported that a tensile stress of 1 MPa caused the volume electrical resistivity to increase by 1.5% for cement paste containing 0.53 vol.% 5-mm long carbon fibers of the same type as used in this work. Since the fibers of this work and of Ref. 10 are not aligned, but are randomly oriented, the above simple calculation only gives an upper bound for the volume fraction of debonded fibers. As suggested by micromechanical analysis, the actual volume fraction of debonded fibers may be roughly taken as 1/2 of the upper bound. Hence, at 1 MPa, 0.0041 vol.% fibers debond, and this debonding causes a volume resistivity increase of 1.5% for the carbon fiber reinforced cement paste. In other words, 0.8% of the fibers debond. Assuming that a debonded fiber does not contribute to electrical conduction in the cement paste, the debonding of 0.8% of the fibers decreases the effective fiber volume fraction from 0.530% to 0.526%. This very small decrease in the effective fiber volume fraction is expected to cause a very small increase in the volume resistivity. The observed small fractional volume resistivity increase of 1.5% is not unreasonable, although it cannot be further substantiated due to insufficient experimental data for the variation of the volume electrical resistivity with fiber volume fraction over this narrow volume fraction range.

The above debonding stress consideration, together with the observation that the contact resistivity increases upon debonding, provide support for the feasibility for the notion that the volume resistivity increase during loading [10] is due to fiber pull-out and the resulting fiber-matrix contact resistivity increase. The distance of fiber pull-out is < 1 μm, as shown by microscopic observation of the crack height [10]. Since the fiber length is 5 mm in Ref. 10, the extent of pull-out is extremely small. Nevertheless, it is sufficient to greatly increase the contact resistivity, thus causing the volume resistivity to increase. Further evidence in support of this notion can be found in Ref. 11.

Conclusion

The contact electrical resistivity between carbon fiber and cement paste decreased with increasing bond strength, and increased during fiber pull-out, both due to the interfacial voids, which are electrically insulating. Evidence is provided in support of the feasibility for the previously reported volume electrical resistivity increase during tensile loading of carbon fiber reinforced cement paste to be due to fiber pull-out.

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