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EFFECT OF POLYMER ADMIXTURES TO CEMENT ON THE BOND STRENGTH AND ELECTRICAL CONTACT RESISTIVITY BETWEEN STEEL FIBER AND CEMENT

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ABSTRACT

The addition of methylcellulose (0.4% by weight of cement) or latex (20% by weight of cement) to cement paste gave similarly significant increases of the shear bond strength between stainless steel fiber and cement paste, in spite of the low concentration of methylcellulose compared to latex. The methylcellulose addition did not affect the contact electrical resistivity between fiber and cement, whereas the latex addition increased this resistivity. Hence, for low cost and low contact resistivity, methylcellulose is preferred to latex. For a given cement paste composition, the bond strength increased linearly with the contact resistivity.

Introduction

Short fibers (such as steel, carbon and polymer fibers) are used in cement for enhancing the flexural toughness and flexural strength and for decreasing the drying shrinkage [1]. The effectiveness of the fiber addition in increasing the flexural strength and decreasing the drying shrinkage depends heavily on the strength of the bond between fiber and cement. It has been shown that the addition of latex (12% by weight of cement) to the cementitious matrix increases the shear bond strength between carbon fiber and the cementitious matrix from 2.1 to 5.9 MPa when the matrix contains silica fume, superplasticizer, antifoam and sand [2]. Although latex is effective for enhancing the bonding, its high content makes the latex addition very costly. Such a high latex content (10-20% by weight of cement) is typical for latex-modified cement, whether with or without fibers, in order to maximise the flexural strength [3,4]. Methylcellulose is a polymer that is much less used in cement than latex, but it is valuable for helping fibers disperse in cement [4,5]. Because methylcellulose is typically used in small amounts (such as 0.4% by weight of cement), methylcellulose addition is much less expensive than latex addition. The effect of methylcellulose addition on the fiber-cement bonding had not been investigated before, so it constitutes the first focus of this paper.

Fibers that are electrically conducting are useful in cement not only for enhancing the mechanical properties, but also for providing smart concrete that can monitor its own strain and damage. The ability to sense reversible strain (at least for the case of cement with short carbon fibers) stems from the increase in electrical contact resistivity between fiber and matrix when the crack-bridging fiber is slightly pulled out upon deformation of the cement-matrix composite [6–9]. The reversible deformation causes a reversible increase in the electrical contact resistivity, which in turn causes a reversible increase in the volume electrical resistivity of the composite. The ability to sense damage stems from the irreversible increase in volume electrical resistivity of the composite upon fiber breakage [6–8] or the irreversible decrease in volume electrical resistivity upon damage of the cement matrix at the junction of adjacent fibers [10]. Fiber breakage is associated with more severe damage than damage of the cement matrix at the junction of adjacent fibers. In addition, electrically conducting fibers are useful in cement for providing electrically conducting cementitious materials [11] that can serve as electrical contacts for smart structures with embedded sensors [12] and for cathodic protection [13] and as electromagnetic interference shields [14]. For all these applications that require electrically conducting fibers, a low contact electrical resistivity between fiber and matrix is desirable. No previous study had been made on the effect of additives (such as polymers, which are less conducting than cement) to the cement matrix on the contact electrical resistivity between fiber and matrix. Such a study therefore constitutes the second focus of this paper.

Experimental Methods

Stainless steel (Fe-Cr-Al) fibers described in Table 1 were used. The as-received fibers were washed in acetone (reagent grade) by stirring the fibers in a beaker containing acetone for 5–10 min. Washing was followed by air drying at room temperature for 10–15 min. (It had been reported that acetone washing of steel rebar increases the bond strength with concrete slightly [15].)

Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. Three types of cement pastes were used, namely (i) plain cement paste (with only cement and water, such that the water/cement ratio is 0.45), (ii) cement paste with methylcellulose in the amount of 0.4% by weight of cement (together with water reducing agent in the amount of 1% by weight of cement, and with water-cement ratio = 0.32), and (iii) cement paste with latex in the amount of 20% by weight of cement (water-cement ratio = 0.23, without water reducing agent). The water reducing agent used in cement paste (ii) was

TABLE 1

Properties of Steel Fibers

Type of steel	Stainless 434
Manufacturer	International Steel Wool Corp. (Springfield, OH)
Length	5 mm
Diameter	60 μm
Density	7.7 $g.cm^3$
Modulus	200 GPa (2.9×10^7 psi)
Elongation at break	3.2%
Tensile strength	970 MPa (1.4×10^5 psi)
Volume electrical resistivity	6×10^{-5} Ω.cm

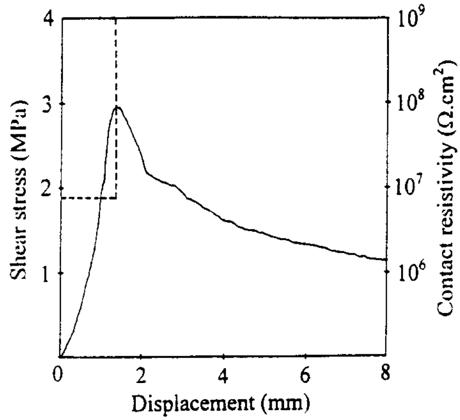

FIG. 1.

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

TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93-96% sodium salt of a condensed naphthalenesulfonic acid. Methycellulose (Dow Chemical, Midland, MI, Methocel A15-LV) in the amount of 0.4% of the cement weight was used in cement paste (ii). The defoamer (Colloids Inc., Marietta, GA, 1010) used along with it was in the amount of 0.13 vol.%; it was used whenever methylcellulose was used. The latex (Dow Chemical, Midland, MI, 460NA used in cement paste (iii) was a styrene-butadiene polymer emulsion; it was used in the amount of 0.20 of the weight of the cement. The antifoam (Dow Corning, Midland, MI, 2410, an emulsion) used was in the amount of 0.5% of the weight of the latex; it was used whenever latex was used.

A Hobart mixer with a flat beater was used for mixing. For the case of mortar containing latex, the latex and antifoam first were mixed by hand for about 1 min. Then this mixture, cement, water and the water reducing agent were mixed in the Hobart mixer for 5 min. For the case of mortar containing methylcellulose, methylcellulose was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Then this mixture, cement, water and water reducing agent were mixed in the Hobart mixer for 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 d and then allowed to cure at room temperature in air for 28 d.

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 of Ref. 9. 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 which was measured for each specimen. The cement paste thickness was 1.5 mm on each side sandwiching the fiber. The fiber length was 5 cm. The current was 0.5-2 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.cm²)

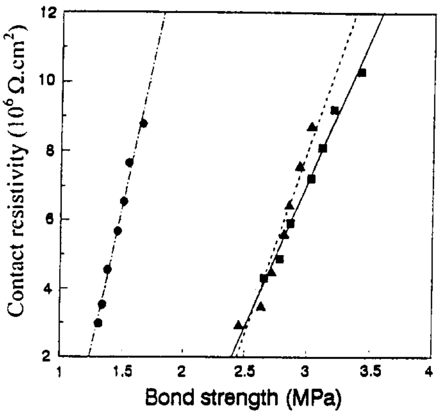

FIG. 2.
Correlation of the contact electrical resistivity with the bond strength for the interface between stainless steel fiber and cement paste at 28 days of curing. ●: plain cement paste; ▲: cement paste with methylcellulose; ■: cement paste with latex.

is given by the product of the contact resistance (in Ω) and in the contact (interface) area (in cm^2).

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 of Ref. 9. 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.

Results

Fig. 1 gives a typical plot of shear stress vs. displacement and a simultaneously obtained plot of contact electrical resistivity vs. displacement. The contact resistivity abruptly increased when the shear stress reached its maximum, i.e., when fiber-matrix debonding was completed. It did not change before the abrupt increase when the shear stress had reached its maximum.

Table 2 and Fig. 2 show the correlation of the contact resistivity with the bond strength. The contact resistivity increased linearly with the bond strength among the data for each type of cement paste (Fig. 2). The bond strength was lower for the plain cement paste than the cement paste with methylcellulose and that with latex. On the average, the paste with latex gave slightly higher bond strength than that with methylcellulose, but the difference was small. On the average, the contact resistivity was higher for the cement paste with latex than the other two pastes, which were similar in contact resistivity.

Discussion

The linear correlation of the bond strength with the contact electrical resistivity for a given cement paste composition (Fig. 2) and the constancy of the contact resistivity during debonding

(Fig. 1) are similar to those reported for the interface between steel rebar and concrete [15]. As explained in Ref. 15, these characteristics are due to an interfacial phase of high volume electrical resistivity that helps the bonding. The linear correlation implies that contact resistivity measurement provides a nondestructive method for measuring the bond strength.

Whether the polymer is latex (20% by weight of cement) or methylcellulose (0.4% by weight of cement), polymer admixtures to the cementitious matrix help the bond between fiber and matrix. In spite of the large difference in concentration between latex and methylcellulose, the effect on the bond strength is similar. On the other hand, methylcellulose addition does not alter the contact electrical resistivity between fiber and matrix, whereas latex addition increases this resistivity. This suggests that the contact resistivity is less sensitive to a small amount of polymer addition than the bond strength is. For the purpose of cost saving and a low contact resistivity, methylcellulose is preferred to latex as an admixture to the cementitious matrix.

The volume resistivity of fiber reinforced cement at a given fiber volume fraction depends on both the degree of fiber dispersion and the fiber-matrix contact resistivity. The degree of fiber dispersion is outside the scope of this paper. Nevertheless, it is interesting to note that the

TABLE 2

Bond Strength and Contact Electrical Resistivity Between Stainless Steel Fiber and Cement Paste

Embedment length (mm, ±0.2)	Bond strength (MPa)	Contact resistivity ($\Omega.cm^2$)
Plain cement paste		
8.2	1.30 ± 0.07	$2.97 \times 10^6 \pm 1 1.1 \times 10^5$
8.1	1.33 ± 0.12	$3.52 \times 10^6 \pm 8.7 \times 10^4$
9.8	1.37 ± 0.21	$4.54 \times 10^6 \pm 7.2 \times 10^4$
11.0	1.45 ± 0.15	$5.67 \times 10^6 \pm 1.5 \times 10^5$
11.6	1.50 ± 0.09	$6.55 \times 10^6 \pm 2.0 \times 10^5$
8.6	1.54 ± 0.05	$7.65 \times 10^6 \pm 6.3 \times 10^4$
9.7	1.65 ± 0.23	$8.78 \times 10^6 \pm 7.8 \times 10^4$
With methylcellulose		
10.2	2.45 ± 0.08	$2.90 \times 10^6 \pm 1.3 \times 10^5$
11.5	2.63 ± 0.10	$3.45 \times 10^6 \pm 7.2 \times 10^4$
11.7	2.71 ± 0.09	$4.48 \times 10^6 \pm 8.1 \times 10^4$
9.8	2.81 ± 0.12	$5.57 \times 10^6 \pm 2.3 \times 10^5$
9.5	2.85 ± 0.15	$6.43 \times 10^6 \pm 3.4 \times 10^5$
10.2	2.93 ± 0.21	$7.56 \times 10^6 \pm 9.2 \times 10^4$
10.5	3.02 ± 0.08	$8.69 \times 10^6 \pm 8.8 \times 10^4$
With latex		
10.7	2.65 ± 0.09	$4.32 \times 10^6 \pm 2.3 \times 10^5$
8.9	2.78 ± 0.06	$4.87 \times 10^6 \pm 1.9 \times 10^5$
11.7	2.86 ± 0.17	$5.92 \times 10^6 \pm 9.2 \times 10^4$
11.5	3.02 ± 0.21	$7.23 \times 10^6 \pm 8.7 \times 10^4$
9.8	3.11 ± 0.15	$8.11 \times 10^6 \pm 3.2 \times 10^5$
9.6	3.20 ± 0.20	$9.22 \times 10^6 \pm 3.0 \times 10^5$
11.6	3.41 ± 0.18	$10.31 \times 10^6 \pm 2.4 \times 10^5$

volume resistivity is much lower for mortar with methylcellulose and 0.24 vol.% carbon fibers than that with latex and 0.37 vol.% carbon fibers [8].

Conclusion

The addition of methylcellulose (0.4% by weight of cement) or latex (20% by weight of cement) to cement paste gave similar increases in the bond strength between stainless steel fiber and cement paste. The methylcellulose addition did not change the contact electrical resistivity between fiber and paste, whereas the latex addition increased this resistivity. For low cost and low contact resistivity, methylcellulose is preferred to latex. For a given cement paste composition, the bond strength increased linearly with the contact electrical resistivity.

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