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SENSITIVITY OF THE BOND STRENGTH TO THE STRUCTURE OF THE INTERFACE BETWEEN REINFORCEMENT AND CEMENT, AND THE VARIABILITY OF THIS STRUCTURE

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ABSTRACT

The variability in interfacial structure and the sensitivity of the bond strength to this variation were studied for each of the interfaces between carbon fiber and cement paste, between stainless steel fiber and cement paste, and between steel rebar and concrete. The interfacial structural variation was indicated by the variation in the contact electrical resistivity. The interface between steel rebar and concrete had least variability but most sensitivity. The interface between carbon fiber and cement paste had less variability but more sensitivity than that between steel fiber and cement paste. *© 1998 Elsevier Science Ltd*

Introduction

The structure of the interface between reinforcement and cement/concrete is characterized by interfacial voids and interfacial phases. This structure affects the bond strength between reinforcement and cement/concrete. Due to the variability of the surface cleanliness of the reinforcement and of the impurity concentrations in the cement/concrete, the interfacial structure varies among interface samples that are identically prepared. This variability causes the bond strength to be also variable. In order to assess the severity of this problem, this paper addresses two questions. Firstly, how variable is the interfacial structure? Secondly, how sensitive is the bond strength to variation in the interfacial structure?

Although the interfacial structure can be studied by microscopy, microscopy is tedious and ineffective for providing a quantitative measure of the global interfacial structure of a given interface sample. On the other hand, the contact electrical resistivity of the interface provides a quantitative and convenient measure of the interfacial structure, as interfacial voids and phases affect the contact resistivity. An increase in interfacial void content decreases the true contact area and hence increases the apparent contact resistivity. Different phases tend to differ in the volume electrical resistivity. For example, iron oxide has a much higher volume resistivity than steel. Thus, a change in the amount of an interfacial phase affects the contact resistivity. Although the effects of the voids and phases on the contact resistivity cannot be

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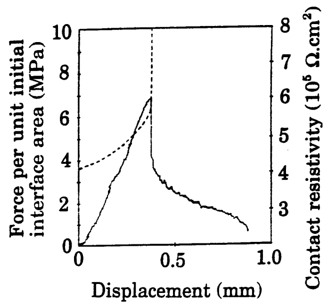

FIG. 1.
Plot of shear force per unit initial interface area vs displacement (solid curve) and of contact electrical resistivity vs displacement (dashed curve) simultaneously obtained during pull-out testing of carbon fiber from cement paste at 28 days of curing.

distinguished, the variability of the contact resistivity provides an indication of the variability of the interfacial structure. This indicator was used in this work.

In order to investigate the sensitivity of the bond strength to variation in the interfacial structure, the bond strength must be correlated with the interfacial structure. Therefore, the bond strength must be measured for every interface sample for which the interfacial structure is analyzed, as done in this work. The interfacial structure variability and the sensitivity of the bond strength to this variation were assessed in this work for the interface between carbon fiber and cement paste, that between stainless steel fiber and cement paste, and that between mild steel rebar and concrete.

Experimental Methods

The carbon fibers were isotropic-pitch-based and unsized, of diameter 15 ± 3 μm, length ~ 5 mm and volume electrical resistivity 3.0×10^{-3} Ω.cm, as obtained from Ashland Petroleum Co. (Ashland, KY). 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. Curing was for 28 days at 40% relative humidity. 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 Figure 1 of Reference 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-voltage relationship was linear. 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 $\Omega.cm^2$) 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.

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 Figure 1 of Reference 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 force during pull-out testing divided by the initial interface area, such that the area depends on the embedment length of the particular sample.

Stainless steel (#434, Fe-Cr-Al) fibers of diameter 60 μm, length ~ 5 mm and volume electrical resistivity 6×10^{-5} Ω.cm, as obtained from International Steel Wool Corp. (Springfield, OH), were also used. Measurements of the bond strength and contact resistivity were performed on the steel fibers in the same way as for the carbon fibers, except that the cement paste (same formulation as for carbon fibers) was embedded the fiber to a distance of 1 cm, the cement paste thickness was 1.5 mm on each side sandwiching the fiber, and the fiber length was 5 cm (1).

The interface between mild steel rebar and concrete was also studied. The rebar was of size #6 (length 26 cm, diameter 1.9 cm, with surface deformations of pitch 2.6 cm).

The concrete was made with Portland cement (as described above), fine aggregate (natural sand, all of which passed through #4 U.S. sieve) and coarse aggregate (all of which passed through 1“ sieve) in the weight ratio 1:1.5:2.49. The water/cement ratio was 0.45 for samples for bond strength testing and 0.50 for samples for corrosion testing. A water reducing agent (as described above) was used in the amount of 2% of the cement weight.

All ingredients were mixed in a stone concrete mixer. Then the concrete mix was poured into a mold, while a steel rebar was positioned vertically at its center. A 6 × 6 × 6 inch (15.2 × 15.2 × 15.2 cm) mold was used. After the pouring of the concrete mix, an external vibrator was applied on the outer surface of the mold. The samples were demolded after 24 h and then cured for 28 days as described above.

Steel pull-out testing was carried out according to ASTM C-234 at 28 days of curing. A hydraulic Materials Testing System (MTS 810) was used at a crosshead speed of 1.27 mm/min. The volume electrical resistivity of the concrete at 28 days was 1.53×10^7 Ω.cm, as obtained by the four-probe method, in which all four probes (silver paint) were around the whole perimeter of the concrete specimen (14 × 4 × 4 cm) in four parallel planes perpendicular to the longest axis of the specimen.

The contact electrical resistivity between the steel rebar and the concrete for bond strength testing was measured at 28 days of curing using the four-probe method and silver paint as electrical contacts, as described above, except that the rebar was used in place of a fiber and concrete instead of cement paste was used as the matrix. Each of one current contact and one voltage contact was circumferentially on the rebar. The other voltage and current contacts were on the concrete embedding the rebar, such that each of these contacts was around the whole perimeter of the concrete in a plane perpendicular to the rebar; the voltage contact was in a plane about 2 inch (5 cm) from the top surface of the concrete, while the current contact was in a plane about 4 inch (10 cm) from the top surface of the concrete. The measured resistance turned out be be dominated by the contact resistance, to the extent that the volume resistance of the rebar can be neglected and that of the concrete cannot. Thus, the volume

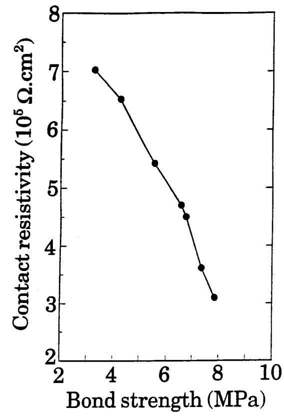

FIG. 2.
Variation of contact electrical resistivity with bond strength for the interface (left) between carbon fiber and cement paste at 28 days of curing.

resistance of the concrete (calculated from the separately measured volume resistivity given above) was subtracted from the measured resistance in order to obtain the contact resistance. The contact area depended on the embedment length, which was separately measured for each sample (2).

Results and Discussion

Figure 1 gives typical plots of shear force per unit initial interface area vs. displacement and of contact resistivity vs. displacement for the interface between carbon fiber and cement paste (3). 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. Figure 2 shows the correlation of the contact electrical resistivity with the bond strength. The contact resistivity decreased with increasing bond strength. This correlation is because poor bonding is associated with a relatively large void content at the interface. The voids are electrically insulating, so they cause the true contact area to decrease and the apparent (measured) contact resistivity to increase. Hence, variation in the apparent contact resistivity is at least partly due to variation in the interfacial void content.

From Figure 2, the maximum change in the apparent contact resistivity is 130% (i.e., (7–3)/3). Since the change in the true contact area cannot exceed 100%, that the maximum change in the apparent contact resistivity exceeds 100% suggests that variation in the true contact resistivity (i.e., contact resistivity of the parts of the interface without voids) occurs. The variation in the true contact resistivity is probably associated with the variation in the surface oxygen concentration. A higher surface oxygen concentration leads to a higher contact resistivity. Both variation in the true contact resistivity and variation in the true contact area contribute to the variation in the apparent contact resistivity. In other words,

$$\left(\frac{\Delta\rho}{\rho}\right)_{\text{apparent}} = \left(\frac{\Delta\rho}{\rho}\right)_{\text{true}} - \left(\frac{\Delta A}{A}\right)_{\text{true}} \tag{1}$$

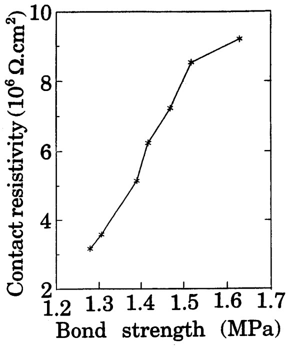

FIG. 3.

Variation of contact electrical resistivity with bond strength for the interface (right) between steel fiber and cement paste at 28 days of curing.

where $(\Delta\rho/\rho)_{apparent}$ is the fractional change in the apparent (measured) contact resistivity (same as the fractional change in the measured contact resistance), $(\Delta\rho/\rho)_{true}$ is the fractional change in the true contact resistivity, and $(\Delta A/A)_{true}$ is the fractional change in the true contact area. Equation 1 means that $(\Delta\rho/\rho)_{apparent}$ is related to the structure of the interface. The term $(\Delta\rho/\rho)_{true}$ is the contribution by the interfacial phases (e.g., surface oxygen); the term $(\Delta A/A)_{true}$ is the contribution by the interfacial voids. Although these two contributions cannot be separately determined, $(\Delta\rho/\rho)_{apparent}$ provides an overall measure of the extent of change in the interfacial structure.

From Figure 2, the maximum change in bond strength due to the maximum change in contact resistivity is −59% (i.e., (3.2–7.9)/7.9). It is negative because the change in bond strength is negative when the change in contact resistivity is positive.

The reciprocal of the slope of Figure 2 relates to the change in bond strength per unit change in contact resistivity. This quantity describes the sensitivity of the bond strength to change in the interfacial structure. More exactly, this sensitivity is defined as the fractional change in bond strength per unit fractional change in contact resistivity. Its value is −0.41 for Figure 2.

Figure 3 shows the correlation of the contact resistivity with the bond strength for the interface between steel fiber and cement paste. The contact resistivity increased with increasing bond strength—a trend which is opposite from that in Figure 2. This trend is because interfacial phase(s) of high volume resistivity help the bond. The more abundant are these phases, the higher is the bond strength and the greater is the contact resistivity. These phases may be iron oxides, but they have not been determined. From Figure 3, the maximum change in the apparent contact resistivity is 190%, the maximum change in bond strength is 26%, and the sensitivity of the bond strength to change in the interfacial structure (from the reciprocal of the slope of Fig. 3) is 0.13.

Figure 4 shows the correlation of the contact resistivity with the bond strength for the interface between steel rebar and concrete. The contact resistivity increased with increasing bond strength, as in Figure 3. From Figure 4, the maximum change in the apparent contact resistivity is 38%, the maximum change in bond strength is 28%, and the sensitivity of the bond strength to change in the interfacial structure is 0.75.

Table 1 summarizes the results for the three types of interfaces studied. The interface

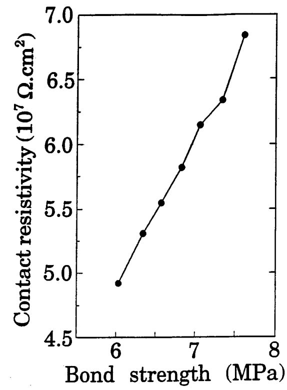

FIG. 4.
Variation of contact electrical resistivity with bond strength for the interface between steel rebar and concrete at 28 days of curing.

between steel rebar and concrete is least variable in interfacial structure (contact resistivity), but has the highest sensitivity of the bond strength to interfacial structural change. The interface between steel fiber and cement is most variable in the interfacial structure, but has the lowest sensitivity of the bond strength to interfacial structural change. The large difference in interfacial structure variability between these two interfaces is probably due to the large difference in size between fiber and rebar. A larger size leads to less variability from sample to sample. The large difference in sensitivity between these two interfaces is probably due to difference in interfacial phase(s). The interfacial phase(s) that help the bond are probably different between stainless steel (fiber) and mild steel (rebar). The difference in sensitivity cannot be explained by the difference in reinforcement shape (surface deformations being present for rebar and absent for fiber), since the presence of surface deformations enhances the bond through mechanical interlocking and hence would have decreased the sensitivity.

Carbon fiber gives less variability in the interfacial structural than steel fiber. This is because of the interfacial voids dominating the interfacial structure between carbon fiber and cement paste, and the interfacial phase(s) dominating the interfacial structure between steel fiber and cement paste, as shown by the difference in trend between Figures 2 and 3. The interfacial phase(s) vary in amount, depending on the surface composition of the fiber.

TABLE 1
Variability in interfacial structure (contact resistivity) and sensitivity of bond strength to interfacial structural change.

Interface	Maximum change in contact resistivity	Maximum change in bond strength	Sensitivity of bond strength to interfacial structural change
Carbon fiber and cement paste	130%	−59%	−0.44
Steel fiber and cement paste	190%	26%	0.13
Steel rebar and concrete	38%	28%	0.75

However, the interfacial voids also vary in amount, mainly depending on the extent of mixing encountered by the fiber (i.e., depending more on how the interface is formed rather than the surface composition of the fiber). On the other hand, the sensitivity (absolute value) is greater for the interface between carbon fiber and cement paste than that between steel fiber and cement paste. This difference is attributed to the bond strength being more sensitive to the interfacial voids than the interfacial phase(s).

Conclusion

This paper provides a study of the variability in interfacial structure and the sensitivity of the bond strength to this variation. The interfacial structure was probed by measuring the contact electrical resistivity. The variability of the contact resistivity reflected the variability of the interfacial structure. The sensitivity of the bond strength to this variation was determined by measuring the fractional change in bond strength per unit fractional change in the contact resistivity. A comparative study was made for the interface between carbon fiber and cement paste, that between stainless steel fiber and cement paste, and that between mild steel rebar and concrete. Among these three interfaces, the interface between steel rebar and concrete had least variability but most sensitivity, whereas the interface between steel fiber and cement paste had most variability but least sensitivity. The interface between carbon fiber and cement paste had less variability but more sensitivity than that between steel fiber and cement paste, due to its being governed by interfacial voids, whereas the interface between steel fiber and cement paste was governed by interfacial phase(s).

Acknowledgment

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