ACI MATERIALS JOURNAL TECHNICAL PAPER

Title no. 95-M72

Effects of Water-Cement Ratio, Curing Age, Silica Fume, Polymer Admixtures, Steel Surface Treatments, and Corrosion on Bond between Concrete and Steel Reinforcing Bars

by Xuli Fu and D. D. L. Chung

The bond between concrete and steel reinforcing bars was evaluated by electromechanical pull-out testing that involved measuring the shear bond strength and contact electrical resistivity of each sample. The bond strength was increased by steel reinforcing bar surface treatment (acetone, water, ozone, or sandblasting, with ozone treatment being the most effective and acetone treatment being the least effective), adding silica fume and polymer to the concrete, an increase in the water-cement ratio of concrete (particularly from 0.45 to 0.50), and a decrease in the curing age (particularly from 14 to 7 days). The origins of these effects are reinforcing bar cleansing for acetone treatment (accompanied by a decrease in contact resistivity), reinforcing bar surface oxide film formation for water and ozone treatments (accompanied by increases in contact resistivity), reinforcing bar surface roughening for sandblasting, polymer interface layer formation for the addition of polymer (accompanied by an increase in contact resistivity for the addition of latex, but not for the addition of methylcellulose), a decreased interfacial void content (accompanied by a decrease in contact resitivity) for an increase in the water-cement ratio (due to an increase in fluidity) and for a decrease in the curing age (due to a decrease in shrinkage), and an increase in the matrix modulus for the addition of silica fume. Corrosion initially caused the bond strength to increase while the contact resistivity increased, but further corrosion caused the bond strength to decrease while the contact resistivity continued to increase.

Keywords: abrasive blasting; bond; cement; concrete; curing age; plastics, polymers and resins.

INTRODUCTION

The bond between concrete and steel reinforcing bars is critical to the effectiveness of steel reinforcement. Therefore, much work has been devoted to improving this bond. The quality of this bond is most commonly described by the shear bond strength, which is measured by pull-out testing.[1]

The difficulty of bond evaluation is related to the variation in the bond quality among samples that are identically prepared. This variation stems from the fact that the steel-concrete interface is not clean like interfaces in electronic devices. This variation results in a large scatter in the data, so it is often difficult to discern the difference in bond strength that results from a difference in bonding condition, concrete design, steel surface treatment, or concrete curing age.

This problem can be alleviated by measuring more than one property on each interface sample, so that the chosen properties are correlated. For example, one property is the bond strength and the other property is the contact electrical resistivity. The plot of one property versus the other for identically prepared samples is a curve, which gives the correlation between the two properties. In other words, all data from identically prepared samples fall on the same curve, which gives information on the nature of the bond.

Upon a change in the sample preparation, the curve changes. By observing how the curve changes, even a small effect on the bond can be discerned. The technique of measuring both bond strength and contact electrical resistivity on each interface sample is hereby called "electromechanical pull-out testing," as it involves measuring the contact resistivity prior to pull-out and measuring the bond strength upon pull-out for the same sample.

By electromechanical pull-out testing, information is obtained about the effects of the water-cement ratio (*w/c*), curing age, polymer admixtures, and steel surface treatments on the bond strength. Moreover, through correlation between bond strength and contact electrical resistivity, the origin of the bond strength change is elucidated. Some of these effects have been previously reported in separate papers.[2-6] This paper combines all these effects to provide a coherent view of

---

ACI Materials Journal, V. 95, No. 6, November-December 1998.
Received July 23, 1997, and reviewed under Institute publication policies. Copyright © 1998, American Concrete Institute. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors. Pertinent discussion will be published in the September-October 1999 *ACI Materials Journal* if received by June 1, 1999.

Xuli Fu is a PhD graduate student in the Department of Mechanical and Aerospace Engineering at the State University of New York at Buffalo, Buffalo, N.Y. He received his MS from Southeast University in the People's Republic of China in 1990, and his PhD from the State University of New York at Buffalo in 1997.

D. D. L. Chung is professor of mechanical and aerospace engineering, Niagara Mohawk Power Corp. Endowed Chair of Materials Research, and Director of Composite Materials Research Laboratory at the State University of New York at Buffalo. She received her PhD in materials science from the Massachusetts Institute of Technology in 1977.

the information that electromechanical pull-out testing has provided on the bond between steel reinforcing bars and concrete. This technique is also applicable to studying the bond between steel fiber and cement paste,[7-9] and that between carbon fiber and cement paste.[10,11]

RESEARCH SIGNIFICANCE

This paper provides information on the effects of *w/c*, curing age, polymer admixtures, steel surface treatments, and corrosion on the bond between concrete and steel reinforcing bars as obtained through electromechanical pull-out testing.

EXPERIMENTAL METHODS

The concrete was made with portland cement (Type I), fine aggregate (natural sand, all of which passed through No. 4 U.S. sieve), and coarse aggregate (all of which passed through 1-in. sieve) in the weight ratio of 1:1.5:2.49. The *w/c* was 0.45, 0.50, 0.55, or 0.60; it was 0.45, unless noted otherwise. A water-reducing agent (sodium salt of a condensed naphthalenesulfonic acid) was used in the amount of 2 percent of the cement weight.

Five types of concrete were used: (1) plain concrete (with only cement, aggregates, and water); (2) concrete with methylcellulose; (3) concrete with latex; (4) concrete with silica fume; and (5) concrete with silica fume and methylcellulose. The concrete was plain concrete, unless noted otherwise. Methylcellulose in the amount of 0.4 percent of the cement weight was used in Concretes (2) and (5). The defoamer used along with it was in the amount of 0.13 volume percent; it was used whenever methylcellulose was used. The latex used in Concrete (3) was a styrene-butadiene copolymer; it was used in the amount of 20 percent of the weight of the cement. The antifoam used was in the amount of 0.5 percent of the weight of the latex; it was used whenever latex was used. Silica fume used in Concretes (4) and (5) was in the amount of 15 percent by weight of cement.

All ingredients were mixed in a stone concrete mixer for 15 to 20 min. Then the concrete mix was poured into a 6 x 6 x 6-in. (15.2 x 15.2 x 15.2-cm) mold, while a steel reinforcing bar was positioned vertically at its center and held in place by protrusion into an indentation at the center of the bottom inside surface of the mold. The mild steel reinforcing bar was of size No. 6, length 260 mm, and diameter 19 mm, and had 90 degree crossed spiral surface deformations of pitch 26 mm and protruded height 1 mm. After the placing of the concrete mix, an external vibrator was applied on the four vertical sides of the mold. Curing of the concrete was allowed to occur in air at a relative humidity (RH) of 40 percent, unless noted otherwise. Steel pull-out testing was carried out according to ASTM C 234 at 7, 14, or 28 days of curing; the curing age was 28 days, unless noted otherwise. A hydraulic material testing system (MTS 810) was used at a crosshead speed of 1.27 mm/min.

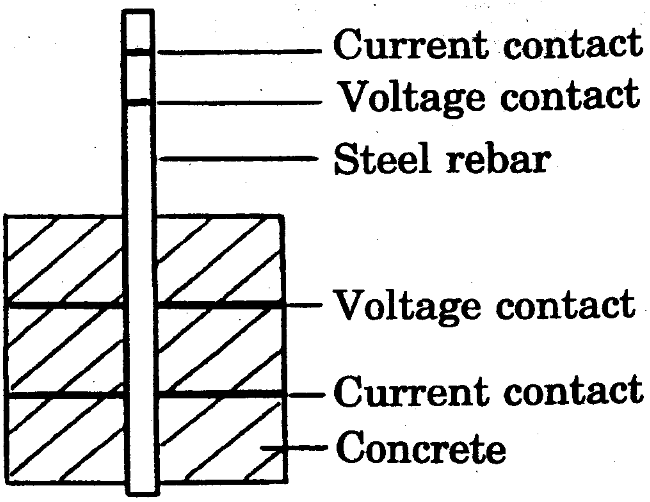

Fig. 1—Sample configuration for measuring contact electrical resistivity and shear bond strength between steel reinforcing bars and concrete.

The volume electrical resistivity of plain concrete at 28 days was 1.53×10^7, 1.51×10^7, 1.50×10^7, and 1.48×10^7 Ω.cm for *w/c* of 0.45, 0.50, 0.55, and 0.60, respectively, at 40 percent *RH* during curing, and was 1.50×10^7, 1.48×10^7, 1.46×10^7, and 1.45×10^7Ωcm for *w/c* ratio of 0.45, 0.50, 0.55, and 0.60, respectively, at 100 percent RH during curing, as obtained by the four-probe method, in which all four probes (silver paint) were around the whole perimeter of the concrete specimen (16 x 4 x 4 cm) in four parallel planes perpendicular to the longest axis of the specimen. The *w/c*, curing age, and *RH* during curing all had negligible effects on the electrical resistivity. The resistivity of concrete with methylcellulose was 1.55×10^7Ω.cm and that of concrete with latex was 2.77×10^7 Ω.cm.

The contact electrical resistivity between the steel reinforcing bars and the concrete was measured using the four-probe method and silver paint as electrical contacts, as illustrated in Fig. 1. One current contact and one voltage contact were circumferentially on the reinforcing bars. The other voltage and current contacts were on the concrete embedding the reinforcing bar, such that each of these contacts was around the whole perimeter of the concrete in a plane perpendicular to the reinforcing bars; the voltage contact was in a plane about 2 in. (51 mm) from the top surface of the concrete, while the current contact was in a plane about 4 in. (102 mm) from the top surface of the concrete. The resistance between the two voltage probes was measured; it corresponds to the sum of the reinforcing bar's volume resistance (the resistance down the length of the reinforcing bar), the steel-concrete contact resistance (the resistance

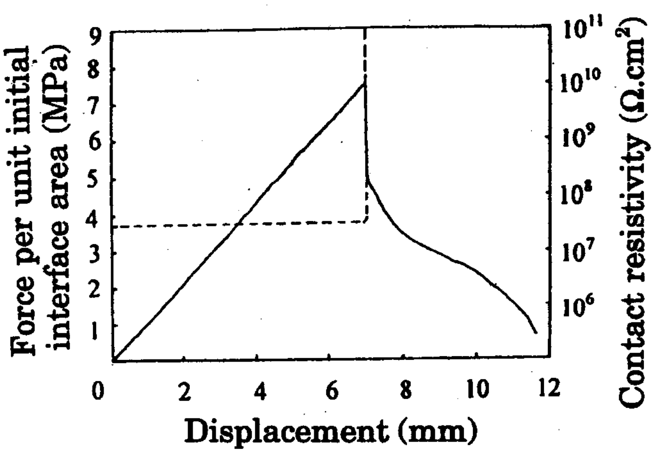

Fig. 2—Shear stress versus displacement (solid curve) and electrical resistivity versus displacement (dashed curve) simultaneously obtained during pull-out testing of as-received steel reinforcing bar from concrete at 28 days.

across the interface), and the concrete volume resistance (the resistance radially outward from the interface to the vertical sides of the concrete). The measured resistance turned out to be dominated by the contact resistance to the extent that the volume resistance of the reinforcing bar can be neglected and that of the concrete cannot. Thus, the volume resistance of the concrete (calculated from the separately measured volume resistivity given above) was subtracted from the measured resistance to obtain the contact resistance. The contact resistivity (in $\Omega.cm^2$) was then given by the product of the contact resistance (in Ω) and the contact area (in cm^2). The contact area depended on the embedment length, which was separately measured for each sample.

Steel pull-out testing was conducted on the same samples and at the same time as the contact resistivity was measured. 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. Fig. 2 is a typical plot of shear force per unit initial interface area versus displacement, and of contact resistivity versus displacement. The contact resistivity abruptly increased when the shear force reached its maximum, i.e., when the steel-concrete debonding was completed. It did not change before this abrupt increase.

The surface treatments given to the steel reinforcing bars were treatments by: (1) acetone (immersion of reinforcing bars in acetone for 15 min, followed by drying in air); (2) water (immersion of reinforcing bars in water for 2, 5, 7, or 10 days, followed by drying in air); (3) ozone (exposure of reinforcing bars to O_3 gas, 0.3 volume percent in air, for 20 min at 160 C, followed by drying at 110 C in air for 50 min); and (4) sandblasting [Al_2O_3 particles, mesh 60 or 250 μm, at 80 psi (0.55 MPa)]. The steel reinforcing bars were as-received, unless noted otherwise.

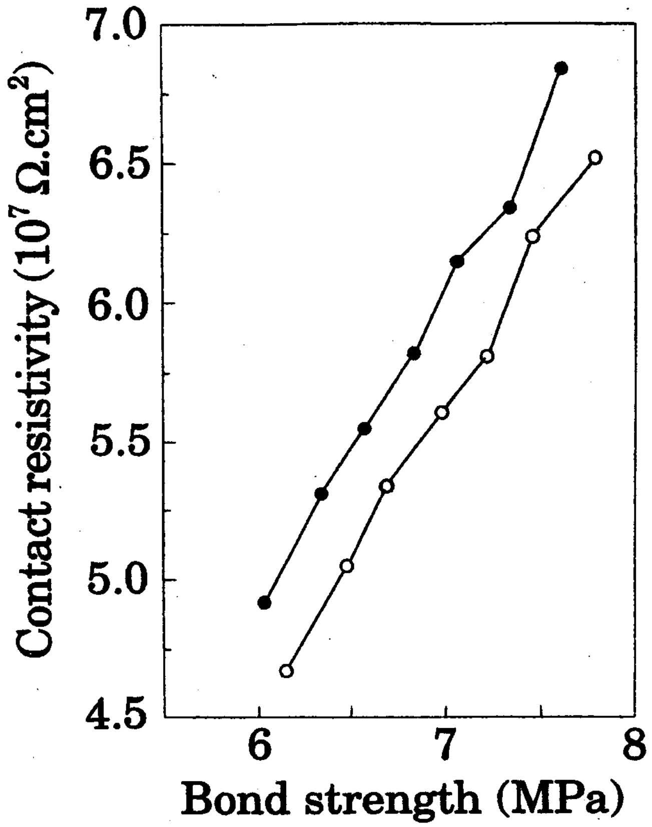

Fig. 3—Variation of contact electrical resistivity with bond strength at 28 days. (Solid circles: as-received steel reinforcing bars; open circles: acetone treated steel reinforcing bars.)

The pull-out samples with as-received steel reinforcing bars in concrete (no admixtures) at 28 days of curing were immersed in saturated $Ca(OH)_2$ solution (resembling the environment in concrete), except for the exposed part of the steel reinforcing bar in each sample. The samples remained in the solution from 1 week to 9 weeks to attain different extents of corrosion of the steel reinforcing bars. At least seven samples were removed from the solution each week, wiped dry and then subjected to electromechanical testing.

At least seven samples were tested for each combination of steel surface treatment, curing age, *w/c*, silica fume admixture, polymer admixture, and extent of corrosion.

RESULTS AND DISCUSSION

Effect of reinforcing bar surface treatment

Fig. 3 through 5 show the correlation of the contact resistivity with the shear force per unit initial interface area for different surface treatments of steel reinforcing bars. The contact resistivity increased roughly linearly with increasing bond strength, such that the data for the different surface treatments lie on essentially parallel straight lines. Acetone treatment increased the bond strength slightly and decreased the contact resistivity slightly (Fig. 3) (as in the case of the interface between stainless steel fiber and cement paste[8]), presumably because of the degreasing action of the acetone. Water immersion for 2 to 5 days (Fig. 4) increased the bond strength by 14 percent (more than for the acetone treatment) and slightly increased the contact resistivity (in contrast to the decrease in contact resistivity for the acetone treatment). Increasing the water immersion time beyond 5 days caused the bond strength to decrease and the contact resistivity to

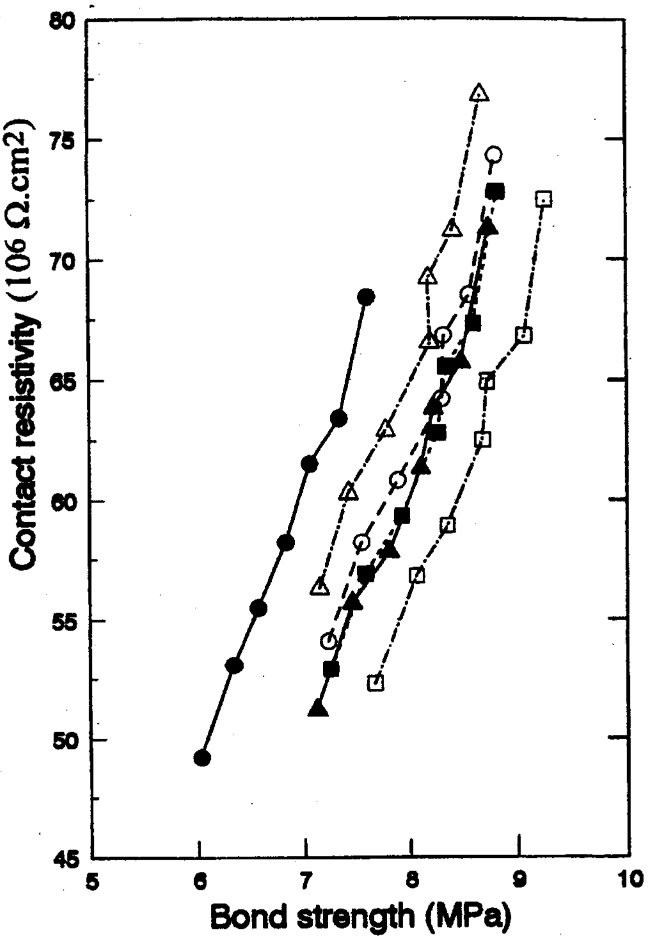

Fig. 4—Variation of contact electrical resisitivity with bond strength at 28 days. (Solid circles: as-received steel reinforcing bars; solid triangles: steel reinforcing bars immersed in water for 2 days; solid squares: steel reinforcing bars immersed in water for 5 days; open circles: steel reinforcing bars immersed in water for 7 days; open triangles: steel reinforcing bars immersed in water for 10 days; open squares: O_3 treated steel reinforcing bars.

increase further (Fig. 4). However, even for a water immersion time of 10 days, the bond strength was still higher than that for the as-received reinforcing bars. Thus, a water immersion time of 2 days is recommended. Fig. 4 shows that ozone treatment enhanced the bond strength more than any of the water treatments. The contact resistivity was also increased by the ozone treatment, but not as much as the water treatment for 7 or 10 days.

It is reasonable to assume that the contact resistivity is related to the amount of the oxidation product at the reinforcing bar-concrete interface, as the oxidation product is a poor electrical conductor. Hence, the differences in contact resistivity (Fig. 4) suggest that the amount of the oxidation product is comparable between O_3 treatment and 2 to 5 day water treatments, but is larger for 7 to 10 day water treatments. The phase of the oxidation product differs between O_3 and water treatments, as indicated by the black color of the oxidation product of the water treatments and the dark gray color of the oxidation product of the O_3 treatment. This phase difference is believed to be partly responsible for the difference in the extent of bond strength enhancement.

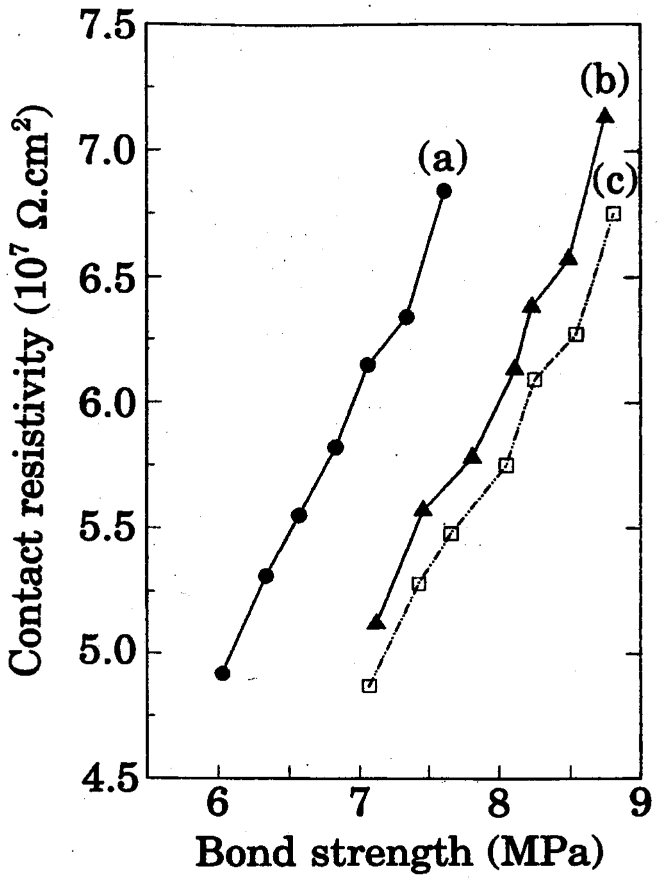

Fig. 5—Variation of contact electrical resistivity with bond strength at 28 days: (a) as-received reinforcing bars; (b) water-treated reinforcing bars; and (c) sandblasted reinforcing bars.

As-received reinforcing bars were all dark gray. After immersion in water for 2 days, a thin layer of black iron oxide formed on the surface of the reinforcing bars. The oxide was hard and thin. The oxidation product was scratched off from the surface, analyzed by x-ray diffraction and found to be amorphous. There was no black oxide formed on the cross-sectional surface of the reinforcing bars after water immersion, so the dark gray coating appeared to come from the native oxide that was formed on the surface of the reinforcing bars while cooling down from hot rolling. The black coating evolved from the dark gray coating. The black oxide powder turned blue in $K_2(CN)_4Fe$ solution, indicating that the oxide contained Fe^{2+}. The black layer was probably hydrated FeO.

The contact resistivity increases with increasing bond strength among the data for each water immersion time (Fig. 4). The origin of this dependence is associated with interfacial phase(s) of volume resistivity higher than that of concrete. The interfacial phase enhances the bonding, unless it is excessive. It may be a metal oxide. Water treatment increases both bond strength and contact resistivity because the treatment forms a black phase that may be akin to rust on the reinforcing bar; the phase enhances the bonding but increases the contact resistivity. The longer the water immersion time, the more the black phase, and the higher the contact resistivity. However, an excessive amount of the black phase (as obtained after 7 or 10 days of water immersion) weakens the bond.

At the same bond strength, the water-treated reinforcing bars exhibits a lower contact resistivity than the as-received reinforcing bars (Fig. 4). The amount of black phase increases with increasing contact resistivity, implying that the black phase formed by the water treatment is more effective than the rust or rust-like phase(s) formed without the water treatment in enhancing the bond strength. The greater effectiveness of the former is probably partly because of the more uniform distribution of the black phase and partly because of the possible difference in phase between the black phase and the rust or rust-like phase formed without the water treatment.

Water treatment and sandblasting increased the bond strength to similar extents (Fig. 5), but were less than that provided by ozone treatment (Fig. 4). Water immersion, like ozone treatment, caused the contact resistivity to increase, but sandblasting had a negligible effect on the contact resistivity. This is consistent with the presence of a black coating on the reinforcing bars after water immersion and the absence of a coating after sandblasting. Scanning electron microscopy (SEM) showed that sandblasting roughened the surface in a coarse way, whereas water treatment resulted in a fine surface microstructure. The uneven surface quality (due to uneven rusting) in the as-received reinforcing bars was removed after sandblasting or water treatment, as shown by visual observation. In spite of the significant roughening by sandblasting, the bond strength was similar for the sandblasted reinforcing bars and the water-treated reinforcing bars. This suggests that the bond strength increase after water immersion is essentially not due to surface roughening, but is due to changes in the surface functional groups (as supported by the black coating) which affect the adhesion between reinforcing bars and concrete.

The use of water and acetone treatments for increasing the bond strength between steel wire and mortar had been previously suggested based on measurement of the flexural strength of steel wire reinforced mortar.[12] The rust that is well adhered to the underlying steel helps the bond between steel reinforcing bars and concrete; as has been reported.[13,14]

Effect of polymer admixtures

Fig. 6 shows the correlation of the contact resistivity with the shear bond strength for different polymer admixtures in the concrete. Polymer admixtures [Curves (b) and (c) of Fig. 6] were slightly less effective than the ozone treatment of the reinforcing bars [Curve (d) of Fig. 6] in increasing the bond strength between the reinforcing bars and concrete (as well as between carbon fiber and cement paste[11]). Between the two polymer admixtures, latex [Curve (c) of Fig. 6] increased the bond strength slightly more significantly than methylcellulose [Curve (b) of Fig. 6], at least partly due to the large amount of latex compared to the amount of methylcellulose. The combined use of latex and the ozone treatment [Curve (e) of Fig. 6] gave significantly higher bond strength than ozone treatment alone [Curve (d) of Fig. 6]. Relative to the combination of plain concrete and untreated reinforcing bars, the combined use of latex and the ozone treatment resulted in a 39 percent increase in the bond strength. Ozone treatment, latex addition, and the combined ozone treatment and latex addition caused similarly small increases in the contact resistivity.

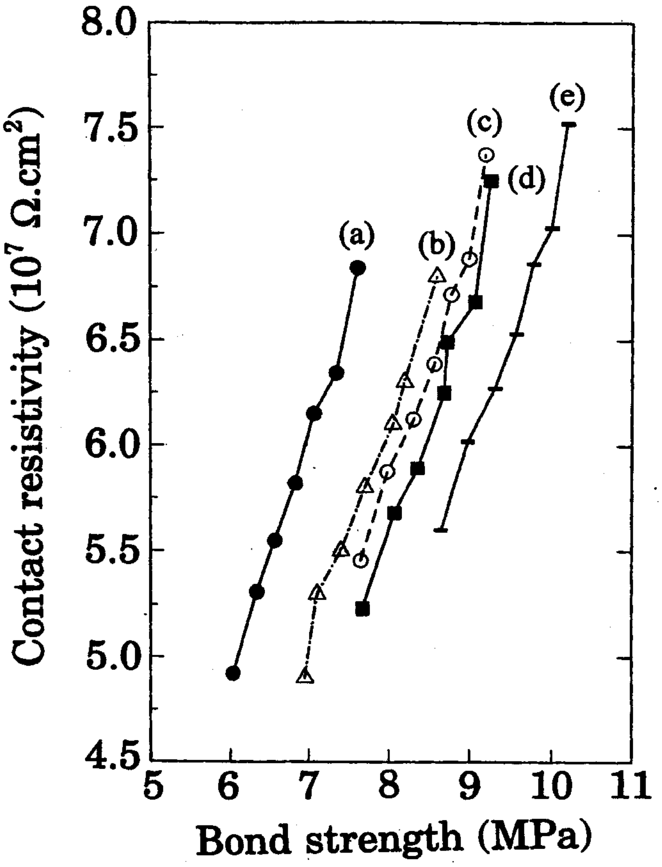

Fig. 6—Variation of contact electrical resistivity with shear bond strength; (a) plain concrete and untreated reinforcing bars; (b) concrete with methylcellulose addition and untreated reinforcing bars; (c) concrete with latex addition and untreated reinforcing bars; (d) plain concrete and ozone-treated reinforcing bars; and (e) concrete with latex addition and ozone-treated reinforcing bars.

The contact resistivity increase after the latex addition is presumably due to the high volume resistivity of the latex at the reinforcing bar-concrete interface. The bond strength increase after the latex or methylcellulose addition is attributed to the adhesion provided by the polymer at the interface. The improved adhesion due to these polymers is indicated, in the case of stainless steel fiber in cement paste, by the increased amount of adherent on the fiber after pull-out from the cement paste, as shown by SEM observation.

In spite of the mechanical interlocking between the reinforcing bars and concrete (due to the surface deformations on the reinforcing bar) that contributes much to the bond strength between the reinforcing bar and concrete (as shown by the much higher bond strength between the reinforcing bars and concrete than that between steel fiber and cement

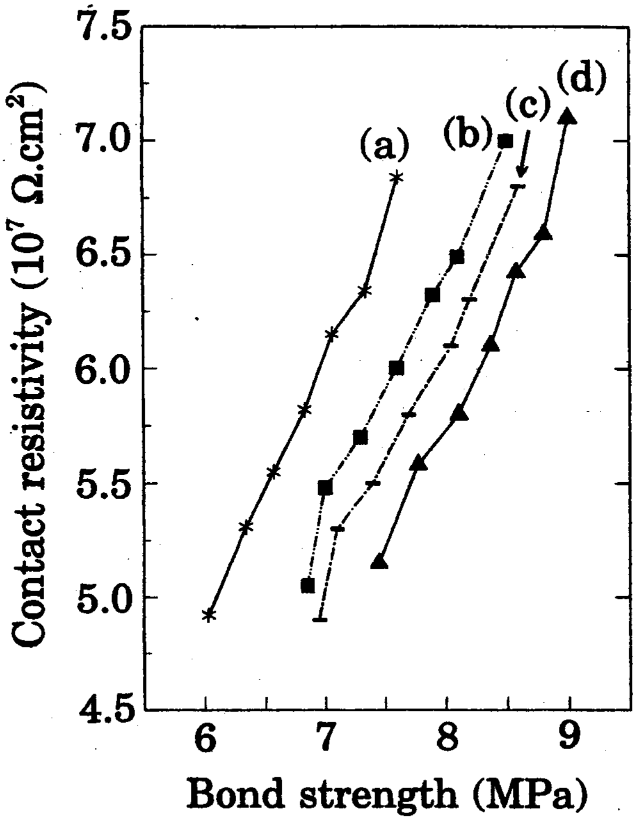

Fig. 7—Variation of contact electrical resistivity with shear bond strength: (a) plain concrete; (b) concrete with silica fume; (c) concrete with methylcellulose; and (d) concrete with silica fume and methylcellulose.

Table 1—Effect of admixtures on tensile properties of cement paste

Admixture	Strength, MPa	Modulus, GPa	Ductility, percent
None*	0.88 (± 4.7 percent)	10.9 (± 3.0 percent)	0.004 (± 1.0 percent)
None†	0.89 (± 3.1 percent)	11.13 (± 2.9 percent)	0.0052 (± 0.9 percent)
Methylcellulose*	1.37 (± 2.3 percent)	6.6 (± 2.1 percent)	0.0209 (± 0.9 percent)
Methylcellulose†	1.38 (± 3.2 percent)	6.89 (± 1.9 percent)	0.0213 (± 0.8 percent)
Methylcellulose + silica fume*	0.83 (± 5.2 percent)	40 (± 1.2 percent)	0.0088 (± 1.1 percent)
Latex*	3.03 (± 4.5 percent)	11.5 (± 2.1 percent)	0.0352 (± 1.2 percent)

* 7 days of curing (from Reference 19).
† 28 days of curing (from Reference 20).

Table 2—Effect of admixtures on flexural properties of cement paste

Admixture	Strength, MPa	Toughness, MPa.mm
None*	2.24 (± 3.2 percent)	0.056
Methylcellulose*	2.29 (± 3.2 percent)	0.105
Methylcellulose + silica fume*	2.79 (± 2.2 percent)	0.193
Latex*	3.62 (± 4.2 percent)	0.202

* 7 days of curing (from Reference 21).

paste[7]), the ozone treatment of the reinforcing bars and the polymer admixtures to the concrete significantly increases the bond strength between the reinforcing bars and concrete. This indicates the importance of interface engineering in improving the bond between the reinforcing bars and concrete. In the case of the bond between stainless steel fiber and cement paste, the polymer admixtures (latex or methylcellulose) in the cement paste cause the bond strength to increase by 90 percent.[7] If the surface deformations on the steel reinforcing bar were absent, the effects of the ozone treatment of the reinforcing bars and of polymer admixtures in concrete would have been much larger than those described in this paper.

This beneficial effect of polymer admixtures on the concrete-concrete bond strength has been previously shown.[15-17] The presence of a polymer interlayer at the cement-aggregate interface has been shown by microscopy to be responsible for the improved adhesion between the cement and aggregate.[18]

Effect of silica fume

Fig. 7 shows the effect of silica fume. Methylcellulose increased the bond strength more than silica fume, while methylcellullose, in combination with silica fume, gave higher bond strength than either silica fume or methylcellulose alone. Silica fume caused a slight increase in contact resistivity, indicating no decrease of the interfacial void content. This means that the increase in bond strength due to the additon of silica fume is not due to the decrease of the interfacial void content.

Tables 1 and 2 show a comparison of the tensile and flexural properties of various cement pastes, as previously reported. Latex gives the most attractive tensile and flexural properties, but is the most expensive due to its large amount (20 percent by weight of cement). Methylcellulose gives low tensile modulus, although its small amount (0.4 percent by weight of cement) makes it economical. With both cost and performance considered, methylcellulose, in combination with silica fume, is the most attractive; it gives a high tensile modulus, tensile ductility, flexural strength, and flexural toughness.

The combined use of latex and silica fume causes the workability to be so low that the resulting paste exhibits very poor mechanical properties. Methylcellulose differs from latex when each is added to the concrete mix in that methylcellulose is in the form of a liquid solution, while latex is in the form of a solid particle dispersion. The liquid form probably allows methylcellulose to be uniformly distributed even when its concentration is low, so that it is effective even at a low concentration. The low concentration, in turn, helps to maintain workability to the mix. On the other hand, the dispersion form of latex results in the need for a high latex concentration in the mix for the latex to be effective.

The effectiveness of silica fume in combination with methylcellulose (as admixtures) is due to the combined effect in

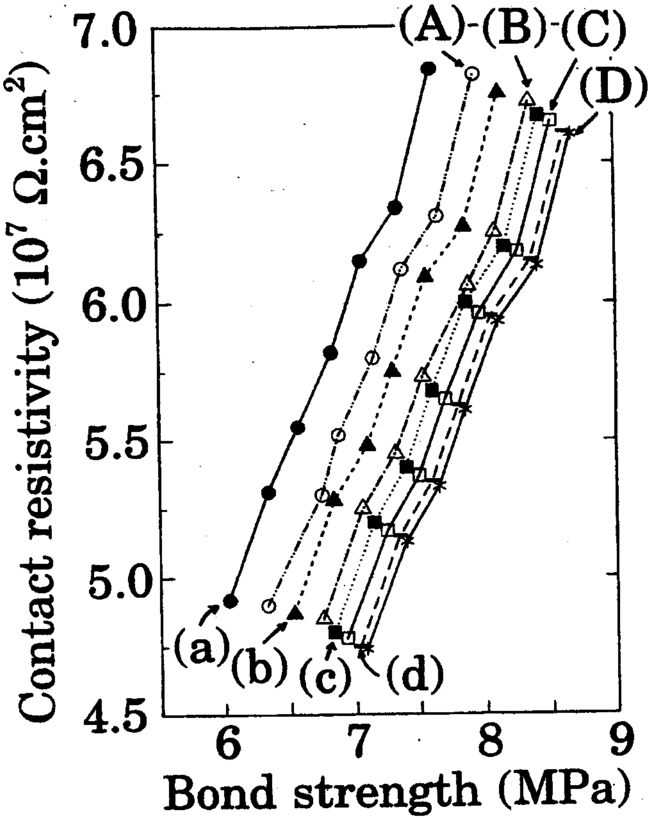

Fig. 8—Variation of contact electrical resistivity with shear bond strength between steel reinforcing bars and concrete with w/c*: (a) 0.45; (b) 0.50; (c) 0.55; and (d) 0.60, (all cured at 40 percent RH) and between steel reinforcing bars and concrete with* w/c*: (A) 0.45; (B) 0.50; (C) 0.55; and (D) 0.60 (all cured at 100 percent RH).*

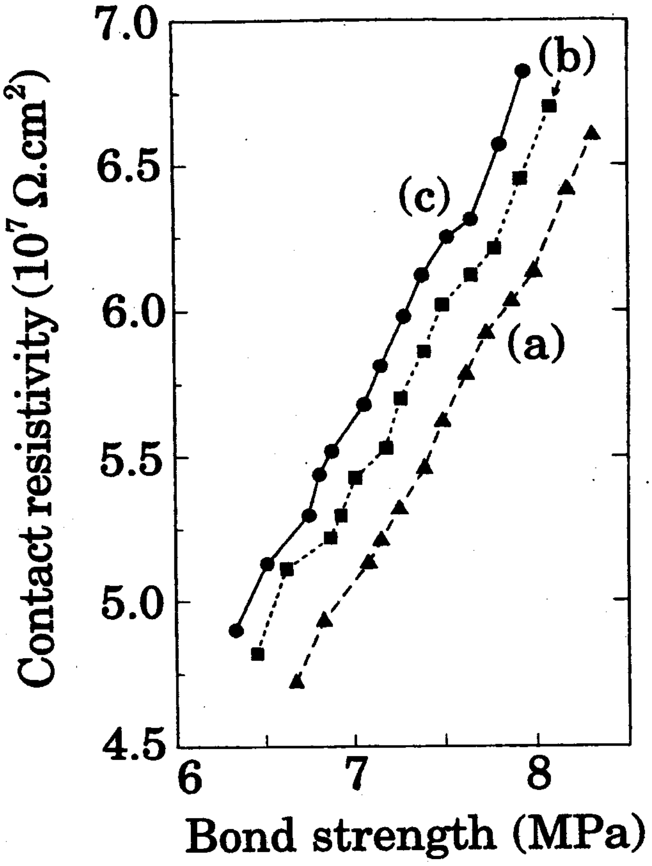

Fig. 9—Variation of contact electrical resistivity with shear bond strength between steel reinforcing bars and concrete with curing age of: (a) 7 days; (b) 14 days; and (c) 28 days, all cured at 100 percent RH.

which silica fume causes an increase in the matrix modulus (rather than interfacial void content decrease) while methylcellulose improves adhesion.

Effect of *w/c* ratio

Fig. 8 shows the correlation of the contact resistivity with the bond strength for values of the *w/c* ranging from 0.45 to 0.60. The greater the *w/c* was, the higher the bond strength was, and the contact resistivity was slightly lower, for each of the two RHs (40 and 100 percent). The increase in bond strength was greatest (fractional increase ~ 7 percent) when the *w/c* was increased from 0.45 to 0.50, less when the *w/c* was increased from 0.50 to 0.55, and still less when the *w/c* was increased from 0.55 to 0.60. For the same *w/c*, the bond strength increased when the humidity was increased from 40 to 100 percent; this effect became smaller as the *w/c* increased.

The increase in bond strength and the decrease in contact resistivity upon increase in the *w/c* are both attributed to the decrease in the interfacial void content. An increase in the *w/c* increased the fluidity of the concrete mix, thereby allowing the mix to fill the gap between the reinforcing bars and concrete more completely. Although an external vibrator was used to help consolidation, the degree of consolidation was not perfect. That the bond strength increased with humidity is consistent with this trend.

Due to the decrease of the compressive strength with increasing *w/c*, increasing the *w/c* for the entire concrete is not practical for most structures. However, the local *w/c* around a steel reinforcing bar was effectively increased in a separate experiment by using a reinforcing bar that had been wetted with water (1 percent weight increase after wetting) just prior to embedding the reinforcing bar in concrete with a *w/c* of 0.45 and curing the concrete at an RH of 40 percent. The use of the wet reinforcing bar indeed resulted in increased bond strength, although the effect was not as much as with increasing the *w/c* from 0.45 to 0.50 or of increasing the RH from 40 to 100 percent.

The finding that the bond strength between the reinforcing bars and concrete increases with an increase in *w/c* is in contrast to the previous notion that the bond strength increases with the tensile or compressive strength of the concrete.[22,23] The compressive strength of concrete is known to decrease with an increase in *w/c* due to an increase in porosity, but the bond strength between steel reinforcing bars and concrete increases with an increase in *w/c* due to a decrease in the interfacial void content. The magnitude of the fractional change in concrete strength is about twice that of the fractional change in bond strength for the same increase in *w/c*. These opposite trends should be taken into account in determining the optimum *w/c* for steel reinforced concrete, especially for

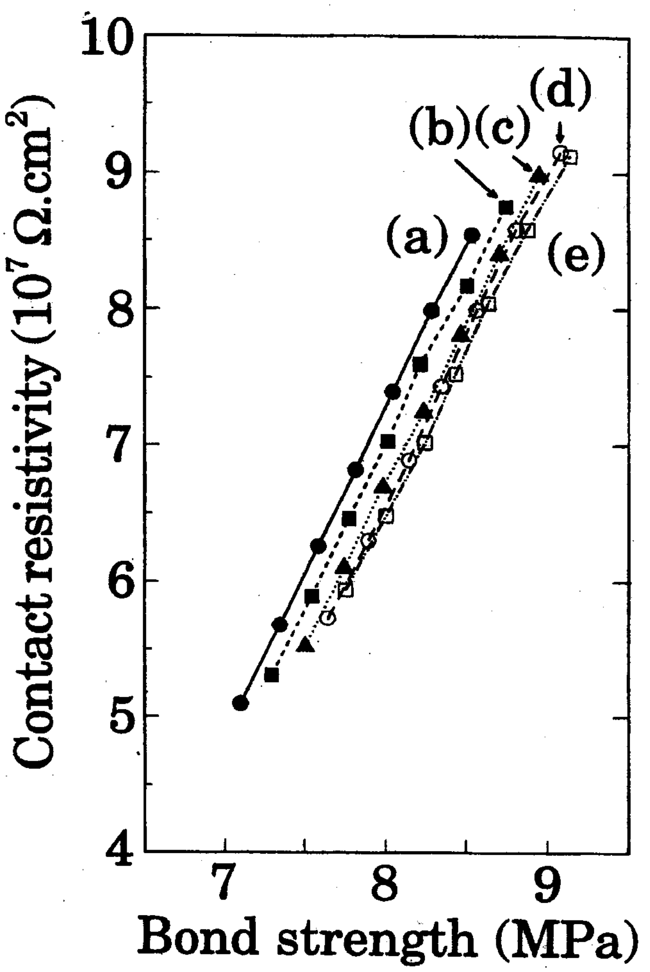

Fig. 10—Variation of contact electrical resistivity with bond strength for as-received steel reinforcing bars in concrete after: (a) 1 week; (b) 2 weeks; (c) 3 weeks; (d) 4 weeks; and (e) 5 weeks of corrosion.

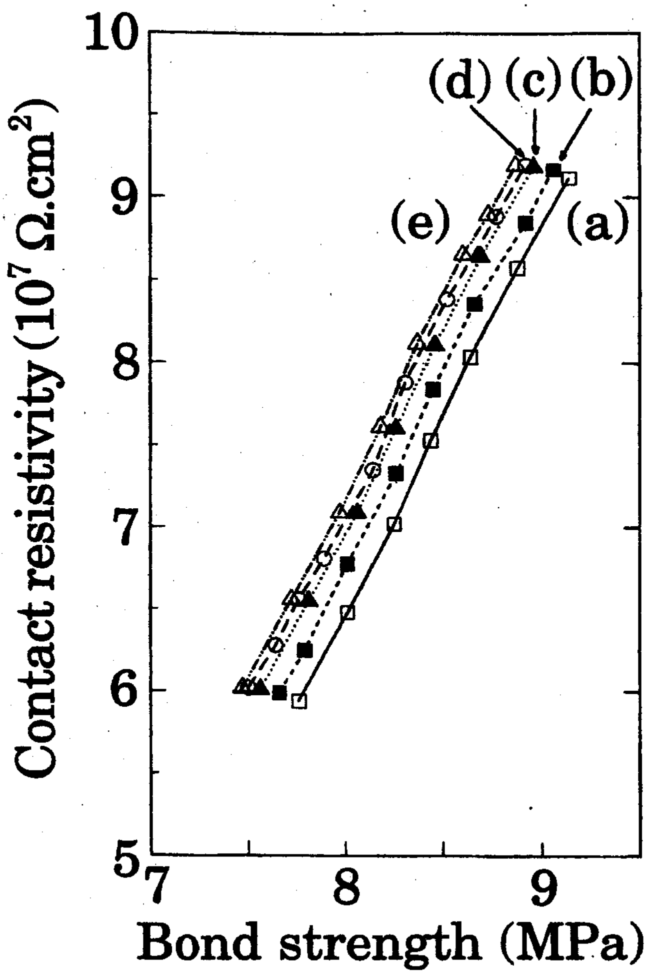

Fig. 11—Variation of contact resistivity with bond strength for as-received steel reinforcing bars in concrete after: (a) 5 weeks; (b) 6 week;, (c) 7 weeks; (d) 8 weeks; and (e) 9 weeks of corrosion.

prefabricated structural components that require a high bond strength. In current practice, the *w/c* is chosen mainly based on consideration of the compressive strength of the concrete. In addition to increasing the bond strength, a high *w/c* reduces the material cost.

Effect of curing age

Fig. 9 shows the correlation of the contact resistivity with the bond strength for different curing ages and curing at 100 percent RH. The greater the curing age was, the lower the bond strength was, and the higher the contact resistivity was. The decrease in bond strength was substantial when the curing age was increased from 7 to 14 days, and less when the curing age was increased from 14 to 28 days. Similar trends were observed for curing at 40 percent RH, but the bond strength at the same curing age was higher at 100 percent RH than at 40 percent RH.

The decrease in bond strength and increase in contact resistivity upon an increase in the curing age are both attributed to the increase in the interfacial void content (or interfacial microcracking). As curing progressed, shrinkage (whether chemical or drying shrinkage) occurred, particularly before 14 days of curing. This shrinkage led to the increase in the interfacial void (or microcrack) content.

The finding that the shear bond strength between the reinforcing bars and concrete decreases with an increase in the curing age is in contrast to the general notion that the bond strength increases with the strength of the concrete. It is also in contrast to the report that the tensile bond strength between concrete and concrete increases with an increase in curing age from 3 to 90 days.[16] However, it is consistent with results on shear bond strength and contact resistivity for the interface between stainless steel fiber and cement paste, obtained also by electromechanical testing.[8]

Effect of corrosion

Fig. 10 and 11 show the curves of contact resistivity versus bond strength after 1 to 9 weeks of corrosion. The bond strength increased as the corrosion time increased from 1 to 5 weeks, such that the increase was relatively significant from 1 to 3 weeks (Fig. 10). However, the bond strength decreased as the corrosion time increased from 5 to 9 weeks, such that the decrease was relatively significant from 5 to 7 weeks (Fig. 11). The contact resistivity increased as the corrosion time

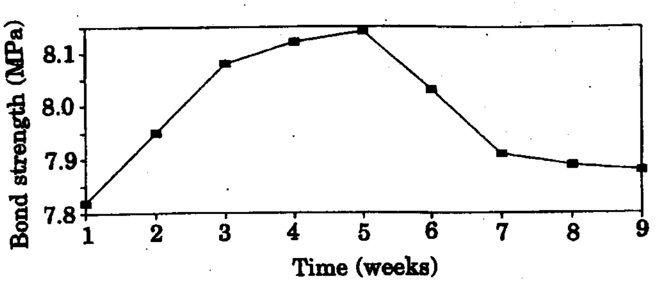

Fig. 12—Variation of bond strength (average value) with corrosion time for as-received steel reinforcing bars in concrete.

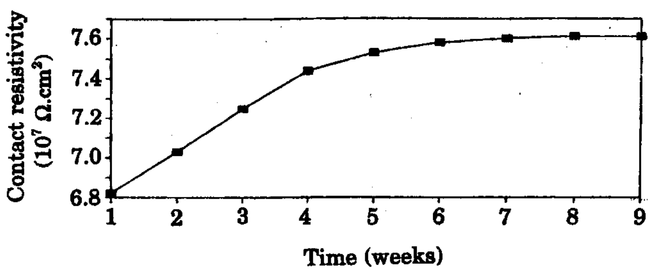

Fig. 13—Variation of contact electrical resistivity (average value) with corrosion time for as-received steel reinforcing bars in concrete.

increased from 1 to 4 weeks (Fig. 10); it increased much more gradually from 4 to 9 weeks (Fig. 10 and 11).

Fig. 12 and 13 show the bond strength (average value for samples of each corrosion time) and contact resistivity (average value for samples of each corrosion time), respectively, during the first 9 weeks of corrosion. Both bond strength and contact resistivity increased as corrosion progressed up to 5 weeks. Beyond 5 weeks of corrosion, the bond strength decreased as corrosion progressed while the contact resistivity continued to increase. This means that the bond strength increased as the steel rusted, but when the rusting was excessive, the bond strength decreased.

This result is consistent with the finding that water immersion of the steel reinforcing bars prior to incorporation in concrete increased the bond strength, but excessive immersion time (beyond 5 days) caused the bond strength to decrease from the high value attained after immersion for 2 to 5 days (Fig. 4). Fig. 13 is also consistent with Fig. 4 in that the contact resistivity increased monotonically with the corrosion time (Fig. 13) or water immersion time (Fig. 4). Fig. 13 also shows that the contact resistivity increased with rusting at the early stage of rusting much more sharply than at the later stage of rusting. This is expected since electron transport by tunneling through an insulator is restricted to a very small distance.

CONCLUSION

By electromechanical pull-out testing, the bond strength between concrete and the steel reinforcing bars was found to increase by the reinforcing bar surface treatment, the silica fume and polymer addition to concrete, an increase in *w/c*, and a decrease in the curing age of concrete. The reinforcing bar surface treatment involving ozone was more effective than those involving water and sandblasting, which were, in turn, more effective than acetone treatment.

Ozone and water treatments worked because of the formation of an oxide film on the reinforcing bar surface (accompanied by an increase in contact resistivity); the oxide film helped the adhesion. Sandblasting worked because of surface roughening and the consequent mechanical interlocking. Acetone treatment worked because of its cleansing of the reinforcing bars (accompanied by a decrease in contact resistivity). Latex addition (20 percent by weight of cement) to concrete was as effective as the ozone treatment of the reinforcing bars in increasing the bond strength; it worked because of the formation of a polymer interface layer that helped the adhesion (accompanied by an increase in contact resistivity). The addition of methylcellulose (0.4 percent by weight of cement) was only slightly less effective than the addition of latex in increasing the bond strength, but it had no effect on the contact resistivity. The addition of silica fume (15 percent by weight of cement) to concrete was less effective than the addition of methylcellulose or latex; it worked because of a modulus increase in the concrete matrix. The combined use of silica fume and methylcellulose was more effective than either silica fume or methylcellulose alone. An increase in the *w/c* (particularly from 0.45 to 0.50) of the concrete increased the bond strength due to the improved fluidity of the concrete mix and the consequent slight decrease in the interfacial void content. An increase of the curing age of the concrete (particularly from 7 to 14 days) decreased the bond strength due to the increased drying shrinkage of concrete and the consequent increase in the interfacial void content. Corrosion initially caused the bond strength to increase while the contact resistivity increased, but futher corrosion caused the bond strength to decrease while the contact resistivity continued to increase.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Foundation.

REFERENCES

1. Windisch, A., "A Modified Pull-Out Test and New Evaluation Methods for a More Real Local Bond-Slip Relationship," *Materiaux et Constructions/Materials and Structures*, V. 18, No. 105, 1985, pp. 181-184.

2. Fu, X., and Chung, D. D. L., "Linear Correlation of Bond Strength and Contact Electrical Resistivity between Steel Rebar and Concrete," *Cement and Concrete Research.*, V. 25, No. 7, 1995, pp. 1397-1402.

3. Fu, X., and Chung, D. D. L., "Improving the Bond Strength between Steel Rebar and Concrete by Oxidation Treatments of the Rebar," *Cement and Concrete Research*, V. 26, No. 10, 1996, pp. 1499-1503.

4. Fu, X., and Chung, D. D. L., "Improving the Bond Strength between Steel Rebar and Concrete by Ozone Treatment of Rebar and Polymer Addition to Concrete," *Cement and Concrete Research*, V. 27, No. 5, 1997, pp. 643-648.

5. Fu, X., and Chung, D. D. L., "Improving the Bond Strength between Steel Rebar and Concrete by Increasing the Water/Cement Ratio of the Concrete," *Cement and Concrete Research*, V. 27, No. 12, 1997, pp. 1805-1809.

6. Hou, J.; Fu, X.; and Chung, D. D. L., "Improving Both Bond Strength and Corrosion Resistance of Steel Rebar in Concrete by Water Immersion or Sandblasting of Rebar," *Cement and Concrete Research*, V. 27, No. 5, 1997, pp. 679-684.

7. Fu, X., and Chung, D. D. L., "Effect of Polymer Admixtures to Cement on the Bond Strength and Electrical Contact Resistivity between

Steel Fiber and Cement," *Cement and Concrete Research*, V. 26, No. 2, 1996, pp. 189-194.

8. Fu, X., and Chung, D. D. L., "Bond Strength and Contact Electrical Resistivity between Cement and Stainless Steel Fiber: Their Correlation and Dependence on Fiber Surface Treatment and Curing Age," *ACI Materials Journal*, V. 94, No. 3, May-June 1997, pp. 203-208.

9. Fu, X., and Chung, D. D. L., "Single Fiber Electromechanical Pull-Out Testing and Its Application to Studying the Interface between Steel Fiber and Cement," *Composites Interfaces*, V. 4, No. 4, 1997, pp. 197-211.

10. Fu, X., and Chung, D. D. L., "Contact Electrical Resistivity between Cement and Carbon Fiber: Its Decrease with Increasing Bond Strength and Its Increase During Fiber Pull-Out," *Cement and Concrete Research*, V. 25, No. 7, 1995, pp. 1391-1396.

11. Fu, X.; Lu, W.; and Chung, D. D. L., "Improving the Bond Strength between Carbon Fiber and Cement by Fiber Surface Treatment and Polymer Addition to Cement Mix," *Cement and Concrete Research*, V. 26, No. 7, 1996, pp. 1007-1012.

12. Mayfield, B., and Zelly, B., "Steel Fibre Treatment to Improve Bonds," *Concrete*, Mar. 1973, pp. 35-37.

13. Murphy, F. G., "The Effect of Initial Rusting on the Bond Performance of Reinforcement," *CIRIA Report* 71, London, 1977, 36 pp.

14. Maslehuddin, M.; Allam, I. M.; Al-Sulaimani, G. J.; Al-Mana, A. I.; and Abduljauwad, S. N., "Effect of Rusting of Reinforcing Steel on Its Mechanical Properties and Bond with Concrete," *ACI Materials Journal*, V. 87, No. 5, Sept.-Oct.,1990, pp. 496-502.

15. ACI Committee 548, "Abstract of: State-of-the-Art Report on Polymer-Modified Concrete," *ACI Materials Journal*, V. 91, No. 5, Sept.-Oct., 1994, pp. 511-520.

16. Walters, D. G., "Latex Hydraulic Cement Additives," *Transportation Research Record* 1204 (Portland Cement Concrete Modifiers), 1988, pp. 71-76.

17. Chen, P.; Fu, X.; and Chung, D. D. L., "Improving the Bonding between Old and New Concrete by the Addition of Carbon Fibers to the New Concrete," *Cement and Concrete Research*, V. 25, No. 3, 1995, pp. 491-496.

18. Sakai, E., and Sugita, J., "Composite Mechanism of Polymer-Modified Cement," *Cement and Concrete Research*, V. 25, No. 1, 1995, pp. 127-135.

19. Chen, P.; Fu, X.; and Chung, D. D. L., "Microstructural and Mechanical Effects of Latex, Methylcellulose and Silica Fume on Carbon Fiber Reinforced Cement," *ACI Materials Journal*, V. 94, No. 2, Mar.-Apr., 1997, pp. 147-155.

20. Fu, X., and Chung, D. D. L., "Effect of Methylcellulose Admixture on the Mechanical Properties of Cement," *Cement and Concrete Research*, V. 26, No. 4, 1996, pp. 535-538.

21. Chen, P., "Carbon Fiber Reinforced Concrete as a Strain/Stress Sensor and High-Performance Civil Structure Material," PhD dissertation, State University of New York at Buffalo, 1994, pp. 50, 52.

22. Hamouine, A., and Lorrain, M., "Pull-Out Strength of Bars Embedded in High Performance Concrete," *Materials and Structures*, V. 28, No. 184, 1995, pp. 569-574.

23. Windisch, A., "Modified Pull-Out Test and New Evaluation Methods for a More Real Local Bond-Slip Relationship," *Materials and Structures*, V. 105, 1985, pp. 181-184.