

## **Interface between steel rebar and concrete, studied by electromechanical pull-out testing**

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**Abstract**—The interface between concrete and steel rebar was evaluated by electromechanical pull-out testing, which involved measuring the shear bond strength and contact electrical resistivity of each sample. The bond strength was increased by steel rebar surface treatment (acetone, water, ozone or sand blasting, with ozone being most effective and acetone being least effective), polymer addition to concrete (methylcellulose or latex), increase in water/cement ratio of concrete (particularly from 0.45 to 0.50), and decrease in curing age (particularly from 14 to 7 days). The origins of these effects are rebar cleansing for acetone treatment, rebar surface oxide film formation for water and ozone treatments, rebar surface roughening for sand blasting, polymer interface layer formation for polymer addition, and decreased interfacial void content for water/cement ratio increase and for curing age decrease.

**Keywords:** Concrete; cement; steel; bond; strength; electrical; polymer; ozone; sand blasting; curing age.

### **1. INTRODUCTION**

Concrete reinforced by steel bars (rebars) is a composite material that has been used in civil structures for decades. In spite of its long history of use, this composite material still needs improvement in terms of the interface between steel rebar and concrete. The interface affects the bond strength between rebar and concrete, in addition to affecting the corrosion resistance of the rebar in the concrete.

The interface between steel rebar and concrete is affected by the surface condition of the rebar and the formulation of the concrete. The study of how these factors affect the interface has been difficult due to variation in interface structure under the same set of conditions. This variation stems from variation in the degree of cleanliness of the interface, as neither the rebar surface nor the concrete constituents are very clean, in sharp contrast to the clean interfaces in semiconductor devices. For example, rust tends to be present on the surface of the steel rebar, whether before

or after embedding the rebar in concrete. The distribution of rust is not uniform on a given rebar and the amount of rust is different from one rebar to another. As a result of this variation, bond strength values determined by pull-out testing under the same sample preparation condition scatter over a substantial range. Under this situation, investigation of the effect of sample preparation condition on the bond strength is difficult.

This problem can be alleviated by electromechanical pull-out testing [1], in which both shear bond strength and contact electrical resistivity are measured on each sample. As both bond strength and contact electrical resistivity are governed by the interface structure, these two quantities are related. From the correlation between these two quantities for a given sample preparation condition, information on the interface structure and origin of adhesion is obtained. A change in sample preparation condition causes the curve that describes this correlation to shift. From the shift in the curve, even a small effect of a change in sample preparation condition on the bond strength and contact electrical resistivity can be observed.

Reference [1] introduced the concept of electromechanical pull-out testing and applied it to studying the interface between steel fiber and cement paste. This paper extends the technique from fiber to rebar and from cement paste to concrete. The fiber and rebar differ not only in size but also in surface topography. The steel fiber has a smooth surface, whereas the steel rebar has 'surface deformations', i.e. ribs or protrusions on the surface to provide mechanical interlocking with the matrix. Cement paste has no aggregate, whereas concrete has both fine aggregate (sand) and coarse aggregate (stones). In spite of these apparent complications with steel rebar and concrete, the electromechanical pull-out testing works just as well as in the case of fiber and cement paste [2–5].

This paper describes the effects of steel rebar surface treatment (acetone, water and ozone treatments and sand blasting) and concrete formulation (variation of the water–cement ratio, the addition of a polymer to the mix and curing age) on the interface between rebar and concrete, as probed by electromechanical pull-out testing.

## 2. EXPERIMENTAL METHODS

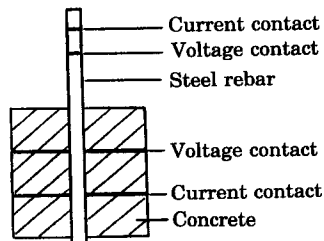
The concrete was made with Portland cement (Type I, from Lafarge Corp., Southfield, MI), fine aggregate (natural sand, all of which passed through #4 US sieve) and coarse aggregate (all of which passed through 1" sieve) in the weight ratio 1 : 1.5 : 2.49. The water/cement ratio was 0.45, 0.50, 0.55 or 0.60; it was 0.45, unless noted otherwise. A water reducing agent (TAMOL SN, Rohm and Haas Co., Philadelphia, PA; sodium salt of a condensed naphthalenesulphonic acid) was used in the amount of 2% of the cement weight. Three types of concrete were used, namely (i) plain concrete (with only cement, aggregates and water); (ii) concrete with methylcellulose; and (iii) concrete with latex. The concrete was plain concrete, unless noted otherwise. Methylcellulose (Dow Chemical, Midland, MI, Methocel

A15-LV) in the amount of 0.4% of the cement weight was used in concrete (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 concrete (iii) was a styrene–butadiene copolymer; it was used in the amount of 20% of the weight of the cement. The antifoam (Dow Corning, Midland, MI, 2210) used was in the amount of 0.5% of the weight of the latex; it was used whenever latex was used.

All ingredients were mixed in a stone concrete mixer for 15–20 min. Then the concrete mix was poured into a  $6 \times 6 \times 6$  in ( $15.2 \times 15.2 \times 15.2$  cm) mold, while a steel rebar was positioned vertically at its center and held in place by protruding into an indentation at the center of the bottom inside surface of the mold. The mild steel rebar was of size #6, length 26 cm, and diameter 1.9 cm, and had  $90^\circ$  crossed spiral surface deformations of pitch 2.6 cm and protruded height 0.1 cm. After the pouring 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 of 40%, 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.

The volume electrical resistivity of plain concrete at 28 days was  $1.53 \times 10^7$ ,  $1.51 \times 10^7$ ,  $1.50 \times 10^7$  and  $1.48 \times 10^7$   $\Omega$  cm for water/cement ratio of 0.45, 0.50, 0.55 and 0.60 respectively, that of concrete with methylcellulose was  $1.55 \times 10^7$   $\Omega$  cm and that of concrete with latex was  $2.77 \times 10^7$   $\Omega$  cm, as obtained by the four-probe method, in which all four probes (silver paint) were around the whole perimeter of the concrete specimen ( $16 \times 4 \times 4$  cm) in four parallel planes perpendicular to the longest axis of the specimen. The water/cement ratio, curing age and relative humidity during curing all had negligible effects on the electrical resistivity.

The contact electrical resistivity between the steel rebar and the concrete was measured using the four-probe method and silver paint as electrical contacts, as illustrated in Fig. 1. 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



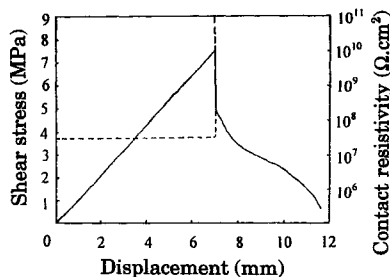
**Figure 1.** Sample configuration for measuring the contact electrical resistivity and shear bond strength between steel rebar and concrete.

contact was in a plane about 2 in (5 cm) from the top surface of the concrete, while the current contact was in a plane about 4 in (10 cm) from the top surface of the concrete. The resistance between the two voltage probes was measured; it corresponds to the sum of the rebar volume resistance (the resistance down the length of the rebar), the steel-concrete contact resistance (the resistance 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 rebar 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 in order to obtain the contact resistance. The contact resistivity (in  $\Omega \text{ cm}^2$ ) was then given by the product of the contact resistance (in  $\Omega$ ) and the contact area (in  $\text{cm}^2$ ). 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. Figure 2 is a typical plot of shear stress vs displacement and of contact resistivity vs displacement. The contact resistivity abruptly increased when the shear stress 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 rebar were treatments by (i) acetone (immersion of rebar in acetone for 15 min, followed by drying in air); (ii) water (immersion of rebar in water for 2, 5, 7 or 10 days, followed by drying in air); (iii) ozone (exposure of rebar to  $\text{O}_3$  gas, 0.3 vol% in air, for 20 min at  $160^\circ\text{C}$ , followed by drying at  $110^\circ\text{C}$  in air for 50 min); and (iv) sand blasting ( $\text{Al}_2\text{O}_3$  particles, mesh 60 or 250  $\mu\text{m}$ , at 80 psi, used with Model S-36-I, Empire Abrasive Equipment, Langhorne, PA). The steel rebars were as-received, unless noted otherwise.

At least seven samples were tested for each combination of steel surface treatment, curing age, water/cement ratio and polymer admixture.

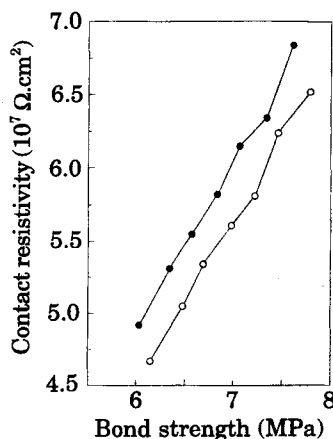


**Figure 2.** Plots of shear stress vs displacement (solid curve) and of contact electrical resistivity vs displacement (dashed curve) simultaneously obtained during pull-out testing of as-received steel rebar from concrete at 28 days.

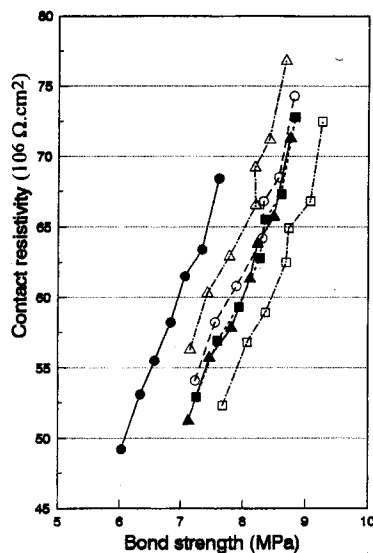
### 3. RESULTS AND DISCUSSION

#### 3.1. Effect of rebar surface treatment

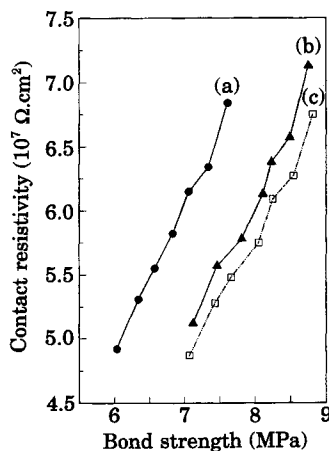
Figures 3–5 show the correlation of the contact resistivity with the shear bond strength for different surface treatments of steel rebar. The contact resistivity increased roughly linearly with increasing bond strength, such that the data for



**Figure 3.** Variation of contact electrical resistivity with bond strength at 28 days. Solid circles: as-received steel rebar. Open circles: acetone treated steel rebar.



**Figure 4.** Variation of contact electrical resistivity with bond strength at 28 days. Solid circles: as-received steel rebar. Solid triangles: steel rebar immersed in water for 2 days. Solid squares: steel rebar immersed in water for 5 days. Open circles: steel rebar immersed in water for 7 days. Open triangles: steel rebar immersed in water for 10 days. Open squares: O<sub>3</sub> treated steel rebar.



**Figure 5.** Variation of contact electrical resistivity with bond strength at 28 days. (a) As-received rebar. (b) Water-treated rebar. (c) Sand blasted rebar.

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 [2]), presumably because of the degreasing action of the acetone. Water immersion for 2–5 days (Fig. 4) increased the bond strength by 14% (more than for acetone treatment) and slightly increased the contact resistivity (in contrast to the decrease in contact resistivity for acetone treatment). Increase of the water immersion time beyond 5 days caused the bond strength to decrease and the contact resistivity to 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 rebar. Thus, a water immersion time of 2 days is recommended. Figure 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 in the case of water treatment for 7 or 10 days.

It is reasonable to assume that the contact resistivity is related to the amount of oxidation product at the rebar–concrete interface, as the oxidation product is a poor electrical conductor. Hence, the differences in contact resistivity (Fig. 4) suggest that the amount of oxidation product is comparable between  $O_3$  treatment and 2–5 day water treatments, but is larger for 7–10 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.

As-received rebars were all dark gray. After immersion in water for two days, a thin layer of black iron oxide formed on the surface of the rebar. 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 rebar after water immersion, so the dark gray coating appeared to come from the native oxide that was formed on the surface of rebar while it was 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 rebar; 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 rebar exhibits a lower contact resistivity than the as-received rebar (Fig. 4). As the amount of black phase increases with increasing contact resistivity, this implies 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 sand blasting increased the bond strength to similar extents (Fig. 5), which were less than that provided by ozone treatment (Fig. 4). Water immersion, like ozone treatment, caused the contact resistivity to increase, but sand blasting had negligible effect on the contact resistivity. This is consistent with the presence of a black coating on the rebar after water immersion and the absence of a coating after sand blasting. Scanning electron microscopy (SEM) showed that sand blasting 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 rebar was removed after sand blasting or water treatment, as shown by visual observation. In spite of the significant roughening by sand blasting, the bond strength was similar for the sand blasted rebar and the water treated rebar. This suggests that the bond strength increase after water immersion is essentially not due to surface roughening, but is due to change in the surface functional groups (as supported by the black coating) which affect the adhesion between rebar and concrete.

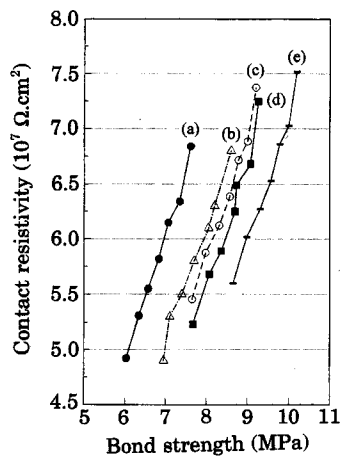
The use of water and acetone treatments for increasing the bond strength between steel wire and mortar had been previously suggested, based on measurement of the flexural strength of steel wire reinforced mortar [6]. That rust which is well adhered to the underlying steel helps the bond between steel rebar and concrete has been reported [7, 8].

### 3.2. Effect of polymer admixtures

Figure 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 ozone treatment of rebar (curve (d) of Fig. 6) in increasing the bond strength between rebar and concrete (as well as that between carbon fiber and cement paste [9]). 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 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 rebar, the combined use of latex and ozone treatment resulted in a 39% increase in the bond strength. Ozone treatment, latex addition and combined ozone treatment and latex addition caused similarly small increases in the contact resistivity.

The contact resistivity increase after latex addition is presumably due to the high volume resistivity of the latex at the rebar–concrete interface. The bond strength increase after 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 fact that the mechanical interlocking between rebar and concrete due to the surface deformations on the rebar contributes much to the bond strength between rebar and concrete (as shown by the much higher bond strength between



**Figure 6.** Variation of contact electrical resistivity with shear bond strength. (a) Plain concrete and untreated rebar. (b) Concrete with methylcellulose addition and untreated rebar. (c) Concrete with latex addition and untreated rebar. (d) Plain concrete and ozone treated rebar. (e) Concrete with latex addition and ozone treated rebar.

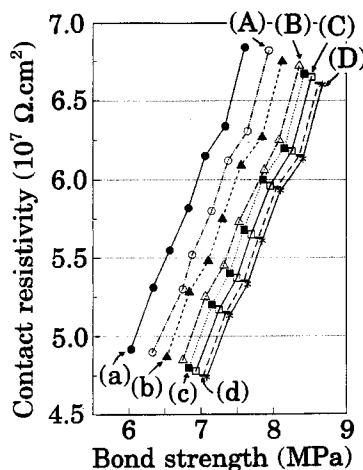


rebar and concrete than that between steel fiber and cement paste [10]), the ozone treatment of the rebar and the polymer admixtures to the concrete give significant increases to the bond strength between rebar and concrete. This indicates the importance of interface engineering in improving the bond between rebar 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% [10]. If the surface deformations on the steel rebar were absent, the effects of ozone treatment of rebar 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 [11–13]. The presence of a polymer interlayer at the cement–aggregate interface has been shown by microscopy to be responsible for the improved adhesion between cement and aggregate [14].

### 3.3. Effect of water/cement ratio

Figure 7 shows the correlation of the contact resistivity with the bond strength for values of the water/cement ratio ranging from 0.45 to 0.60. The greater was the water/cement ratio, the higher was the bond strength, and the slightly lower was the contact resistivity, for each of the two relative humidities (40 and 100%). The increase in bond strength was greatest (fractional increase  $\sim 7\%$ ) when the water/cement ratio was increased from 0.45 to 0.50, less when the ratio was increased from 0.50 to 0.55, and still less when the ratio was increased from 0.55 to 0.60. For the same water/cement ratio, the bond strength increased when



**Figure 7.** Variation of contact electrical resistivity with shear bond strength between steel rebar and concrete of water/cement ratio (a) 0.45; (b) 0.50; (c) 0.55 and (d) 0.60; all cured at 40% relative humidity, and between steel rebar and concrete of water/cement ratio (A) 0.45; (B) 0.50; (C) 0.55; and (D) 0.60; all cured at 100% relative humidity.

the humidity was increased from 40 to 100%; this effect became smaller as the water/cement ratio increased.

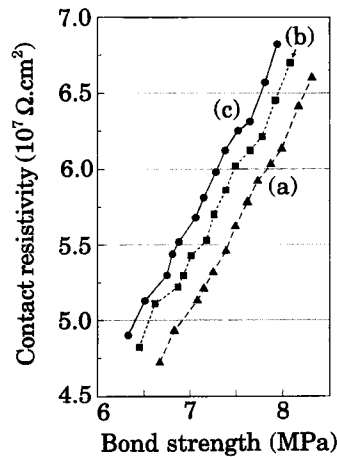
The increase in bond strength and the decrease in contact resistivity upon increase in the water/cement ratio are both attributed to the decrease in the interfacial void content. An increase in the water/cement ratio increased the fluidity of the concrete mix, thereby allowing the mix to fill the gap between rebar 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 water/cement ratio, increasing the water/cement ratio for the entire concrete is not practical for most structures. However, the local water/cement ratio around a steel rebar was effectively increased in a separate experiment in this work by using a rebar which had been wetted with water (1% weight increase after wetting) just prior to embedding the rebar in concrete of water/cement ratio 0.45 and curing the concrete at a relative humidity of 40%. The use of the wet rebar indeed resulted in increased bond strength, although the effect was not as much as that of increasing the water/cement ratio from 0.45 to 0.50 or that of increasing the relative humidity from 40 to 100%.

The finding that the bond strength between rebar and concrete increases with increasing water/cement ratio is in contrast to the previous notion that the bond strength increases with the tensile or compressive strength of the concrete [15, 16]. The compressive strength of concrete is known to decrease with increasing water/cement ratio, but the bond strength between steel rebar and concrete increases with increasing water/cement ratio. 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 water/cement ratio. These opposite trends should be taken into account in determining the optimum water/cement ratio for steel reinforced concrete, especially for prefabricated structural components that require a high bond strength. In current practice, the water/cement ratio is chosen mainly based on consideration of the compressive strength of the concrete. In addition to increasing the bond strength, a high water/cement ratio reduces the material cost.

### *3.4. Effect of curing age*

Figure 8 shows the correlation of the contact resistivity with the bond strength for different curing ages and curing at 100% relative humidity. The greater was the curing age, the lower was the bond strength, and the higher was the contact resistivity. 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% relative humidity, but the bond strength at the same curing age was higher at 100% relative humidity than at 40% relative humidity.



**Figure 8.** Variation of contact electrical resistivity with shear bond strength between steel rebar and concrete of curing age (a) 7 days; (b) 14 days; and (c) 28 days; all cured at 100% relative humidity.

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

The finding that the shear bond strength between rebar and concrete decreases with increasing 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 curing age from 3 to 90 days [12]. 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 [1].

#### 4. CONCLUSION

By electromechanical pull-out testing, the bond strength between concrete and steel rebar was found to be increased by rebar surface treatment, polymer addition to concrete, increase in water/cement ratio and decrease in curing age of concrete. Rebar surface treatment involving ozone was more effective than those involving water and sand blasting, which were in turn more effective than acetone treatment. Ozone and water treatments worked because of the formation of an oxide film on the rebar surface; the oxide film helped the adhesion. Sand blasting worked because of surface roughening and the consequent mechanical interlocking. Acetone treatment worked because of its cleansing of the rebar. Latex addition (20% by weight of cement) to concrete was as effective as ozone treatment of rebar in increasing the bond strength; it worked because of the formation of a polymer interface layer which helped the adhesion. Methylcellulose addition (0.4% by weight of cement) was only

slightly less effective than latex addition in increasing the bond strength. Increase of the water/cement ratio (particularly from 0.45 to 0.50) of the concrete increased the bond strength, due to improved fluidity of concrete mix and the consequent slight decrease in the interfacial void content. Increase of the curing age of the concrete (particularly from 7 to 14 days) decreased the bond strength, due to drying shrinkage of concrete and the consequent increase in the interfacial void content.

### Acknowledgement

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