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EFFECT OF CORROSION ON THE BOND BETWEEN CONCRETE AND STEEL REBAR

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ABSTRACT

The effect of corrosion on the bond between concrete and steel rebar was studied by measuring both bond strength and contact electrical resistivity. Corrosion of steel rebar in concrete immersed in saturated $Ca(OH)_2$ solution was found to cause the bond strength to increase, and the contact resistivity increased until 5 weeks of corrosion. Further corrosion caused the bond strength to decrease, while the contact resistivity continued to increase. *© 1997 Elsevier Science Ltd*

Introduction

Corrosion is one of the main causes for the limited durability of steel-reinforced concrete. The corrosion product, rust, resides at the interface between steel rebar and concrete, thus degrading the bond between steel rebar and concrete. However, rust that is well adhered to the underlying steel helps the bond between steel and concrete (1,2). Moreover, surface treatment of the steel with water to form a coating, prior to incorporation of the steel in concrete, increases the bond strength (3,4). In addition, the contact electrical resistivity between steel rebar and concrete increases with bond strength, suggesting that the interfacial phase (rust or a phase akin to rust) helps the bond (4–6).

To clarify the effect of corrosion on the bond between steel and concrete, we report here a systematic study of both bond strength and contact resistivity as a function of corrosion time of steel-reinforced concrete. The contact resistivity is a quantity that increases monotonically with an increasing amount of interfacial phase (rust), because the interfacial phase has a much higher volume electrical resistivity than steel and most likely a higher resistivity than concrete as well. Therefore, the contact resistivity provides a better indication of the extent of corrosion than does the corrosion time. The correlation of bond strength and contact resistivity provides a correlation of bond strength and the extent of corrosion.

For the same corrosion time, different samples can be different in bond strength and contact resistivity, because different samples can have different degrees of cleanliness at the interface, even prior to corrosion. This problem of data scatter can be alleviated by measuring

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both bond strength and contact resistivity for every sample and observing the correlation between these two quantities among samples of the same corrosion time. The curve describing this correlation shifts with corrosion time, thus allowing the effect of corrosion on the bond strength to be clearly determined in spite of the data scatter. The method of measuring both contact resistivity and bond strength for the same sample is called "electromechanical pull-out testing," which has been applied previously to studying the effects of steel surface treatments, polymer admixtures, water/cement ratio, and curing age on the bond between steel and concrete (4–13).

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 a #4 U.S. sieve), and coarse aggregate (all of which passed through a 1-inch sieve) in the weight ratio 1:1.5:2.49. The water/cement ratio was 0.45. 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. The concrete was plain concrete (with only cement, aggregates, and water).

All ingredients were mixed in a stone concrete mixer for 15–20 min. Then the concrete mix was poured into a $6 \times 6 \times 6$ inch ($15.2 \times 15.2 \times 15.2$ cm) mold, and 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 size #6, length 26 cm, and diameter 1.9 cm, and had 90° crossed spiral surface deformations of pitch 2.6 cm and a protruded height of 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%. Steel pull-out testing was carried out according to ASTM C-234. A hydraulic Material Testing System (MTS 810) was used at a crosshead speed of 1.27 mm/min.

The volume electrical resistivity of 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 ($16 \times 4 \times 4$ cm) in four parallel planes perpendicular to the longest axis of the specimen. The curing age had negligible effects on the electrical resistivity, especially after 28 days of curing.

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 Figure 1 of Ref. 5. Each current contact and each 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 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 could be neglected and that

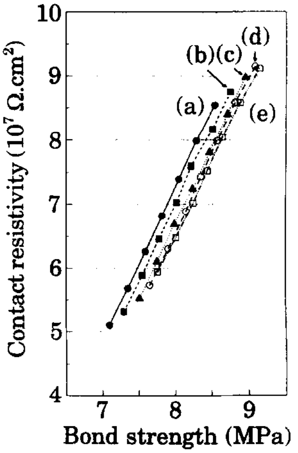

FIG. 1.
Variation of contact electrical resistivity with bond strength after (*a*) 1 week, (*b*) 2 weeks, (*c*) 3 weeks, (*d*) 4 weeks, and (*e*) 5 weeks of corrosion.

of the concrete could not. 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 Ω·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

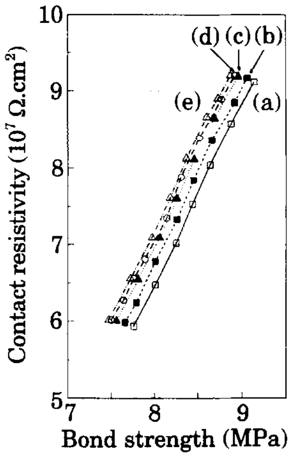

FIG. 2.
Variation of contact resistivity with bond strength after (*a*) 5 weeks, (*b*) 6 weeks, (*c*) 7 weeks, (*d*) 8 weeks, and (*e*) 9 weeks of corrosion.

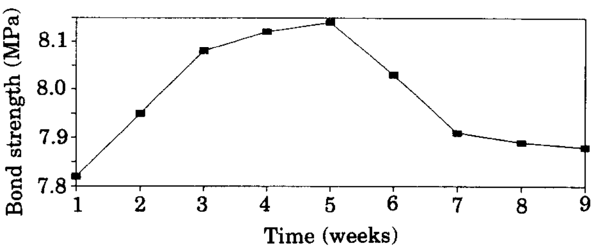

FIG. 3.
Variation of bond strength (average value) with corrosion time for as-received steel rebar in concrete.

testing. Figure 2 of Ref. 5 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 pull-out samples with as-received steel rebars 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 rebar in each sample. The samples remained in the solution for times ranging from 1 to 9 weeks in order to attain different extents of corrosion of the embedded steel rebars. At least seven samples were removed from the solution each week, wiped dry, and then subjected to electromechanical testing.

Results and Discussion

Figures 1 and 2 show the curves of contact resistivity vs bond strength after 1 to 9 weeks of corrosion. The bond strength increased with increasing corrosion time from 1 to 5 weeks, such that the increase was relatively significant from 1 to 3 weeks (Fig. 1). However, the bond strength decreased with increasing corrosion time from 5 to 9 weeks, such that the decrease was relatively significant from 5 to 7 weeks (Fig. 2). The contact resistivity increased with increasing corrosion time from 1 to 4 weeks relatively significantly (Fig. 1); it increased much more gradually from 4 to 9 weeks (Fig. 1 and 2).

Figures 3 and 4 show the bond strength (average value for samples of each corrosion time)

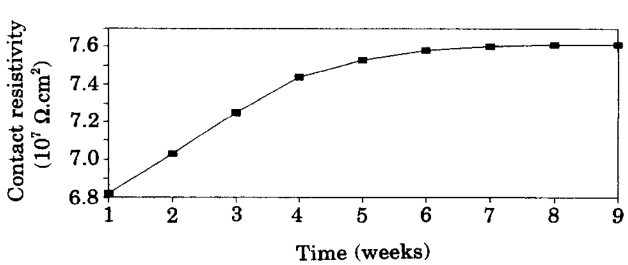

FIG. 4.
Variation of contact electrical resistivity (average value) with corrosion time for as-received steel rebar in concrete.

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, whereas 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 steel rebar 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 (4). Figure 4 is also consistent with Ref. 4 in that the contact resistivity increased monotonically with corrosion time (Fig. 4) or water immersion time (4). Figure 4 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 inasmuch as electron transport by tunneling through an insulator is restricted to a very small distance.

Conclusion

Corrosion of steel rebar in concrete immersed in saturated $Ca(OH)_2$ solution was found to initially cause the bond strength to increase while the contact resistivity increased. This behavior persisted until 5 weeks of corrosion. Further corrosion, beyond 5 weeks, caused the bond strength to decrease while the contact resistivity continued to increase. This means that slight corrosion (<5 weeks) increased the bond strength, whereas severe corrosion (>5 weeks) decreased the bond strength.

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