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IMPROVING BOTH BOND STRENGTH AND CORROSION RESISTANCE OF STEEL REBAR IN CONCRETE BY WATER IMMERSION OR SAND BLASTING OF REBAR

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ABSTRACT

Water immersion (2 days) and sand blasting were similarly effective for treating steel rebars for the purpose of improvement steel-concrete bond strength and corrosion resistance of steel in concrete. The increase in bond strength is due to surface roughening in the case of sand blasting and the presence of a surface layer in the case of water immersion. The increase in corrosion resistance is due to the surface uniformity rendered by either treatment. © *1997 Elsevier Science Ltd*

Introduction

The bond strength between steel rebar and concrete is critical to the structural performance of steel reinforced concrete. The corrosion resistance of steel rebar in concrete greatly affects the durability of steel reinforced concrete. Water treatment (by immersion of rebar in water at room temperature for 2 days) and ozone treatment have recently been shown to be effective for increasing the bond strength between rebar and concrete [1]. Sand blasting has been used for cleansing (removing the rust or both contaminants from) the surface of rebars prior to the use of the rebars in laboratory studies [2], although it is too expensive for use in the field during construction. No work has been previously reported concerning the effects of these rebar treatments on the corrosion resistance of the rebar in concrete. In this work, we found that water immersion and sand blasting are comparatively effective for increasing both bond strength and corrosion resistance of rebar in concrete. Since water immersion is inexpensive, it is particularly suitable for practical implementation.

Experimental Methods

The concrete was made with Portland cement (Type I, from Lefarge Corp., Southfield, MI), 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 (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 for samples for bond strength testing, but not used for samples for corrosion testing.

Mild steel rebars of size #6 were used for bond strength testing and those of size #3 were used for corrosion testing. The #6 rebars were of length 26 cm and diameter 1.9 cm, with surface deformations of pitch 2.6 cm. The #3 rebars were of length 23 cm and diameter 0.92 cm, with surface deformations of pitch 0.6 cm.

Rebars with three different kinds of surface conditions were tested. They were as-received rebars, water treated rebars and sand blasted rebars. The sand blasting equipment used was the Model S-36-I (Empire Abrasive Equipment Co., 2101 W. Cabot Blvd., Langhorne, PA 19047). Al_2O_3 particles with mesh size 60 (250 μm) at 80 psi was used for blasting. The water treated rebars refer to rebars which had undergone a surface treatment involving total immersion of the rebars (without sand blasting) in water for 2 days at room temperature. (Water immersion times less than or greater than 2 days gave less desirable effects on both corrosion resistance and bond strength, so only results for a water immersion time of 2 days are reported here.) Three samples were tested for each treatment condition.

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 in (15.2 × 15.2 × 15.2 cm) mold was used for samples for bond strength testing; a cylindrical mold of diameter 7.8 cm and height 15 cm was used for samples for corrosion testing. 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 in air with a relative humidity of 33% for 28 days.

Steel pull-out testing was carried out according to ASTM C-234 at 28 days of curing. A hydraulic Material Testing System (MTS 810) was used at a crosshead speed of 1.27 mm/min. The volume electrical resistivity of the concrete for bond strength testing 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 illustrated in Fig. 1 of Ref. 3. 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 in (5 cm) from the top surface of the concrete, while the current contact was in a plane about

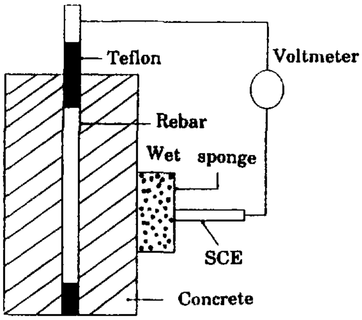

FIG. 1.
Schematic of steel reinforced concrete sample under corrosion testing. SCE = saturated calomel electrode.

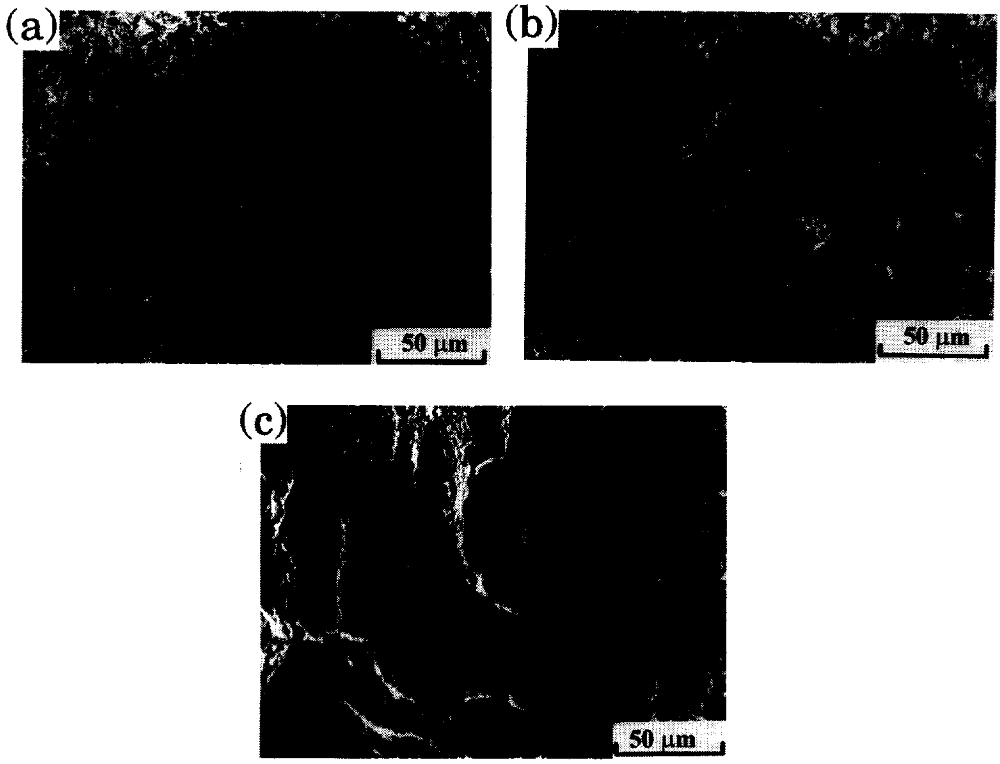

FIG. 2.
SEM photographs of (a) as-received rebar, (b) water treated rebar and (c) sand blasted rebar.

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, such 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 $\Omega.cm^2$) 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. Refer to Fig. 2 of Ref. 3 for typical plots 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. Seven samples were tested for each interface condition.

The corrosion potential (E_{corr}) and polarization resistance of the rebar in concrete were measured in 0.5 N NaCl solution to study the effect of different treatments of rebar on the corrosion resistance of rebar in the concrete. The common advantage of the two tests is that they are both nondestructive methods that are suitable for long-term corrosion monitoring.

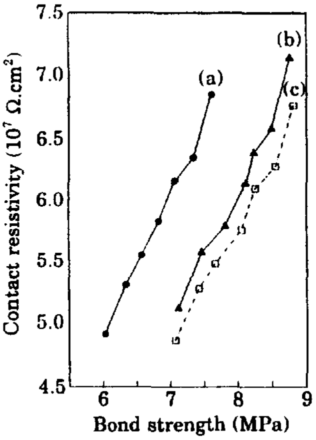

FIG. 3.

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

Concretes have variable and high values of the volume electrical resistivity (of the order of 10^6 Ω.cm). This results in a high IR drop which, coupled to other factors, give rise to ill-defined regions of passivity in practical anodic polarization curves. Therefore, no polarization curve was recorded.

A testing method for measuring E_{corr} of concrete is specified in ASTM C876. The E_{corr} was measured periodically using a high impedance voltmeter and a saturated calomel electrode (SCE) with tip diameter 2 mm and glass casing diameter 1.5 cm. Fig. 1 is a schematic drawing of the test set-up. Teflon tape was locally wrapped around the rebar (Fig. 1) in order to clearly define the rebar-concrete interface area under study. The SCE was put on the cylindrical surface of the concrete through a piece of wet sponge of thickness 2 cm before squeezing and 2 mm after squeezing, which occurred by pressure application during the experiment. The area of the sponge in close contact with the concrete surface was 2 cm in diameter. The samples were tested once a week for 5 weeks in NaCl solution. According to ASTM C876, E_{corr} that is more negative than-270 mV suggests 90% probability of active corrosion in concrete.

The polarization resistance (R_p) test was used to measure the polarization resistance and the corrosion current density (I_{corr}). Because of the high electrical resistance of concrete, an extremely low scan rate (0.167 mV/s) was required to obtain a meaningful result. Furthermore, due to the high electrical resistance of concrete, the current involved in the polarization test was low. Thus, a shield made of copper wire mesh was applied to the whole testing apparatus in order to reduce the noise. At least 24 hours passed between each successive polarization test in order to allow the sample to become stable electrochemically.

The I_{corr} of rebar in concrete at equilibrium was calculated from the relationship developed by Stern and Geary [3], of which the following is a simplification:

$$I_{corr} = B/R_p \tag{1}$$

where B is a constant for a given system. A typical value of B for concrete is 26 mV [3].

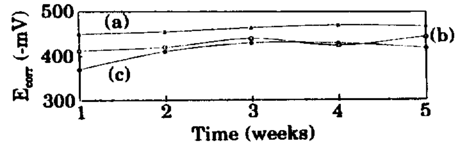

FIG. 4.
Corrosion potential of (a) as-received rebar, (b) water treated rebar, and (c) sand blasted rebar.

Results and Discussion

Scanning electron microscopy (SEM) (Fig. 2) 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.

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 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.

Fig. 3 shows the effect of water immersion and sand blasting on the shear bond strength and contact electrical resistivity. Both treatments increased the bond strength to similar extents, which were less than that provided by ozone treatment [1]. Water immersion, like ozone treatment, caused the contact resistivity to increase, as previously reported [1], 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. 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 (as supported by Fig. 1), but is due to change in the surface functional groups (as supported by the black coating) which affect the adhesion between rebar and concrete.

Fig. 4 shows the E_{corr} versus time curve for the plain concrete with as-received, sand blasted and water treated rebars, all in 0.5 N NaCl solution. Fig. 5 shows the corresponding I_{corr} versus time curves. Both water immersion and sand blasting caused E_{corr} to be less negative and decreased I_{corr}, indicating improvement in the corrosion resistance to similar degrees. The improvement in both cases is attributed to the fact that either treatment rendered the rebar

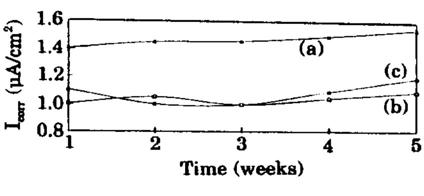

FIG. 5.
Corrosion current density of (a) as-received rebar, (b) water treated rebar, and (c) sand blasted rebar.

surface uniform, in contrast to the non-uniformity due to uneven rusting in the as-received case. The uniformity reduced the number of microscopic corrosion cells, thereby improving the corrosion resistance. On the other hand, a fundamental difference between the effects of the two treatments is that water treated rebars were passive before embedment in concrete, whereas sand blasted rebars became passive after embedment in concrete.

Conclusion

Water immersion (2 days) and sand blasting were similarly effective for treating steel rebars for the purpose of improving steel-concrete bond strength and corrosion resistance of steel in concrete. The increase in bond strength is due to surface roughening in the case of sand blasting and the presence of a surface layer in the case of water immersion. The increase in corrosion resistance is due to the surface uniformity rendered by either treatment. Due to low cost, water immersion is more practically attractive than sand blasting.

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