Pergamon

Cement and Concrete Research, Vol. 27, No. 5, pp. 643-648, 1997

0008-8846/97 $17.00 + .00

PII S0008-8846(97)00057-4

COMMUNICATED PAPERS

IMPROVING THE BOND STRENGTH BETWEEN STEEL REBAR AND CONCRETE BY OZONE TREATMENT OF REBAR AND POLYMER ADDITION TO CONCRETE

Xuli Fu and D.D.L. Chung
Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400, USA

(Communicated by D.M. Roy)
(Received December 20, 1996; in final form March 24, 1997)

ABSTRACT

Ozone treatment of steel rebar, together with latex addition (20% by weight of cement) to concrete, resulted in a 39% increase in the shear bond strength between rebar and concrete, compared to a 25% increase resulted from either ozone treatment alone or latex addition alone. Ozone treatment and latex addition resulted in similarly small increases in the contact electrical resistivity between rebar and concrete. Methylcellulose addition (0.4% by weight of cement) to concrete gave slightly less bond strength increase than the latex addition, but did not affect the contact resistivity. © *1997 Elsevier Science Ltd*

Introduction

The quality of the bond between steel rebar and concrete is critical to the effectiveness of steel reinforcement in concrete. The bond strength between steel rebar and concrete is reduced by the presence of an epoxy coating on the steel (1-4), though the epoxy coating helps to improve the corrosion resistance of the steel rebar. Polymer admixtures, such as latex and methylcellulose, in the cement paste increase the bond strength between stainless steel fiber and cement paste (5) and that between carbon fiber and cement paste (6,7). Oxidation treatments (using either water or ozone) of steel rebar increase the bond strength between rebar and concrete, such that ozone treatment gives more bond strength increase than water treatment (8). Oxidation treatment (using ozone) of carbon fiber increases the bond strength between carbon fiber and cement paste to a value higher than that attained by polymer admixtures (6). These findings indicate the importance of interface engineering in improving the bond between reinforcement and cement. This paper extends the prior interface engineering work to increase the bond strength between steel rebar and concrete. Specific questions that remain to be answered concerning the improvement of the bond strength between steel and concrete include the following. Firstly, what is the effect of polymer admixtures compared to that of ozone treatment of rebar on the bond strength between rebar and concrete? Secondly, how much is the effect of combined use of polymer admixture and ozone treatment of rebar on the bond strength between rebar and concrete? This paper addresses these two questions, thereby increasing the bond strength between rebar and concrete by up to 39%.

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. 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, (ii) concrete with methylcellulose, and (iii) concrete with latex. 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, 2410) 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 × 6 × 6 in (15.2 × 15.2 × 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° 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 33%. 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 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 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. 9. 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 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

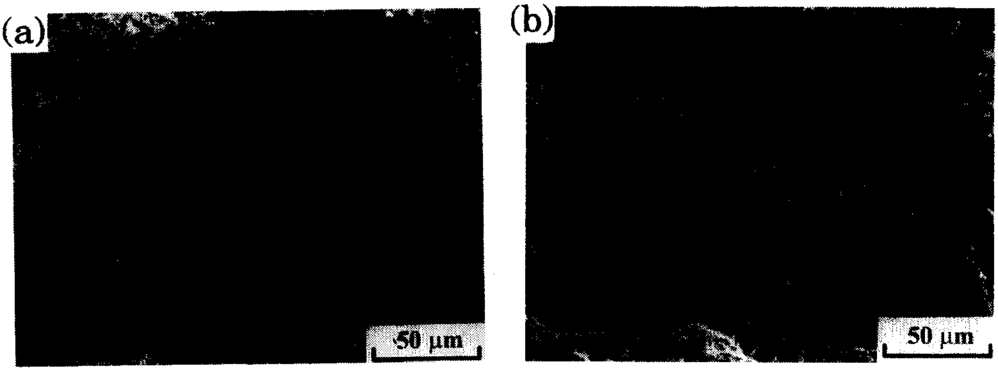

FIG. 1.
Scanning electron microscope photographs of the rebar (a) before and (b) after ozone treatment.

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 testing. Refer to Fig. 2 of Ref. 9 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 five interface conditions are listed in Table 1.

Ozone treatment of steel rebars was conducted by exposure to O_3 gas (0.3 vol.%, in air) for 20 min at 160°C. Prior to O_3 exposure, the rebars had been dried at 110°C in air for 50 min. The ozone treatment increased the degree of coarse roughness of the rebar surface, as shown by the scanning electron microscope (SEM) photographs of the region between the surface

TABLE 1

Bond Strength and Contact Resistivity Ranges for Each of Five Combinations of Concrete and Rebar

Curve in Fig. 2	Concrete	Rebar	Contact resistivity (10^7 Ω.cm^2)	Bond strength (MPa)
(a)	Plain	Untreated	5.85 ± 0.93	6.83 ± 0.80
(b)	Methylcellulose	Untreated	5.81 ± 0.91	7.71 ± 0.76
(c)	Latex'	Untreated	6.40 ± 0.95	8.50 ± 0.85
(d)	Plain	Ozone-treated	6.21 ± 0.98	8.55 ± 0.88
(e)	Latex	Ozone-treated	6.55 ± 0.95	9.50 ± 0.85

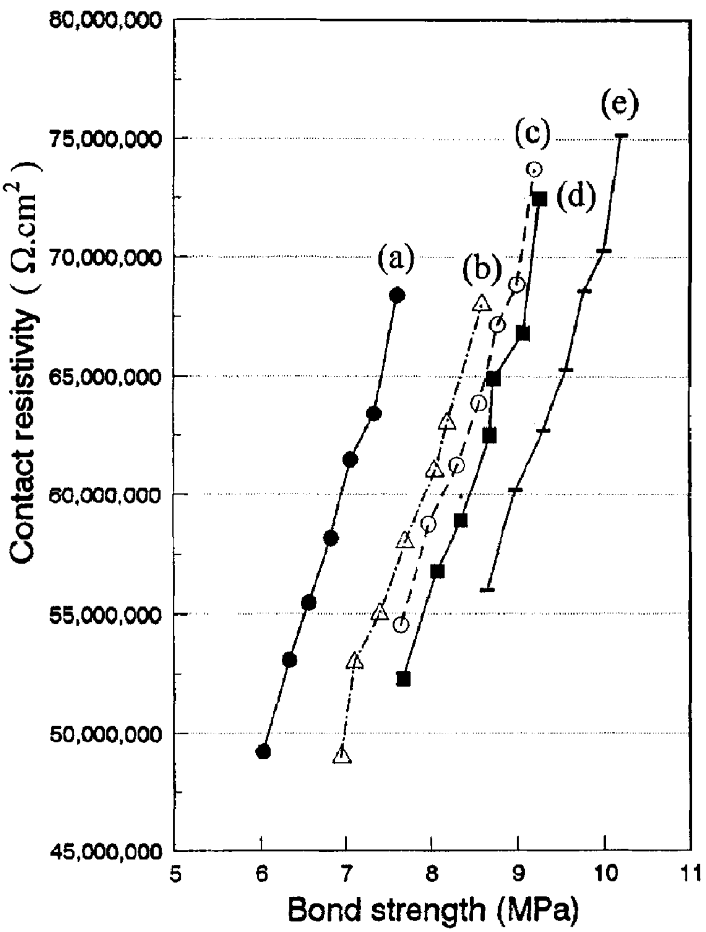

FIG. 2.
Variation of contact electrical resistivity with shear bond strength. (a) Plain concrete and untreated rebar. (b) Concrete with methylcellulose addition and untreated rebar. (c) Concrete with latex addition and untreated rebar. (d) Plain concrete and ozone treated rebar. (e) Concrete with latex addition and ozone treated rebar.

deformations of the rebar before (as received) and after ozone treatment (Fig. 1). The surface roughness was not uniform for the as-received rebar, due to rust on parts of the rebar. Fig. 1(a) was taken from an area of the as-received rebar without apparent rust. After ozone treatment, the surface roughness was uniform.

Results and Discussion

Fig. 2 shows the correlation of the contact resistivity with the shear bond strength. The contact resistivity increased roughly linearly with increasing bond strength (as in Ref. 9), such that the data for the different rebar treatments and polymer admixtures lie on essentially parallel straight lines. Table 1 lists the ranges of bond strength and contact resistivity for each of the five combinations of rebar and concrete in Fig. 2. The shifts of the curves relative to one another in Fig. 1 give more accurate comparison of the bond strengths for the various combinations than the value ranges in Table 1 do. Polymer admixtures (curves (b) and (c) of Fig. 2) were slightly less effective than ozone treatment of rebar (curve (d) of Fig. 2) in increasing the bond strength between rebar and concrete (as well as that between carbon fiber and cement paste (6)). Between the two polymer admixtures, latex (curve (c) of Fig. 2) increased the bond strength slightly more significantly than methylcellulose (curve (b) of Fig. 2), 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. 2) gave significantly higher bond strength than ozone treatment alone (curve (d) of Fig. 2). 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 ozone treatment is due to the dark grey and uniform oxide layer (presumably of high volume electrical resistivity) formed by ozone treatment on the rebar surface. The bond strength increase after ozone treatment is attributed partly to this layer and partly to the effect of ozone treatment on the surface roughness. 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 (10).

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 rebar and concrete than that between steel fiber and cement paste (5)), 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 of methylcellulose) in the cement paste cause the bond strength to increase by 90% [5]. 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.

Conclusion

Ozone treatment of steel rebar, together with latex addition to concrete, resulted in a 39% increase in the shear bond strength between rebar and concrete, compared to a 25% increase resulted from either ozone treatment alone or latex addition alone. Ozone treatment and latex addition resulted in similarly small increases in the contact resistivity between rebar and concrete. Methylcellulose addition to concrete gave slightly less bond strength increase than latex addition, but did not affect the contact resistivity.

Acknowledgments

This work was supported by National Science Foundation. The authors thank Mr. Weiming Lu and Ms. Jiangyuan Hou of the State University of New York at Buffalo for technical assistance.

References

1. John Cairns and Ramli Abdullah, ACI Mater. J. 91(4), 331 (1994).
2. A.R. Cusens and Z. Yu, Structural Engineer 71(7), 117 (1993).
3. David Darwin, Steven L. McCabe, Hossain Hadje-Ghaffari and Oan Chul Choi, Serv. Durability Constr. Mater., Proc. First Mater. Eng. Congr., edited by Bruce A. Suprenant, published by ASCE, New York, NY, 1990, 115-123.
4. Bilal S. Hamad and James O. Jirsa, Ibid, 125-134.
5. Xuli Fu and D.D.L. Chung, Cem. Concr. Res. 26(2), 189 (1996).
6. Xuli Fu and D.D.L. Chung, Cem. Concr. Res. 26(7), 1007 (1996).
7. Parviz Soroushian, Fadhel Aouadi and Mohamad Nagi, ACI Mater. J. 88(1), 11 (1991).
8. Xuli Fu and D.D.L. Chung, Cem. Concr. Res. 26 (1996).
9. Xuli Fu and D.D.L. Chung, Cem. Concr. Res. 25, 1397 (1995).
10. Xuli Fu and D.D.L. Chung, unpublished result.