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LINEAR CORRELATION OF BOND STRENGTH AND CONTACT ELECTRICAL RESISTIVITY BETWEEN STEEL REBAR AND CONCRETE

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ABSTRACT

The bond strength and contact electrical resistivity between steel rebar and concrete were found to be linearly related, due to an interfacial phase of high volume resistivity that helps the bonding. Acetone washing of the rebar increases the bond strength slightly and decreases the contact resistivity slightly, but does not affect the linear correlation, which provides a nondestructive method for bond strength assessment.

Introduction

The bond strength between steel rebars and concrete is critical to the effectiveness of the rebars in reinforcing the concrete. Measurement of the bond strength is commonly made by pull-out testing. Because pull-out testing destroys the bond, it cannot be applied in the field for testing the bond strength between a chosen steel rebar and concrete. A nondestructive method is needed. Microscopy is nondestructive, but it cannot provide bond strength assessment.

The authors have previously shown that the bond strength between a stainless steel fiber and cement paste is linearly related to the contact electrical resistivity [1,2], so that contact electrical resistivity measurement provides a nondestructive technique for assessing the bond strength. In this paper, we report that the same linear relationship applies to the bond between a steel rebar (rather than steel fiber) and concrete (rather than cement paste).

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. All ingredients were

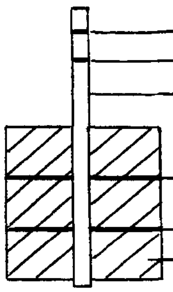

Fig. 1
Sample configuration for measuring the contact electrical resistivity and shear bond strength between steel rebar and concrete.

mixed in a stone concrete mixer for 15-20 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 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 x 4 x 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. 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 current was 0.5-2 A; the voltage was 3-4 V. 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 Ω.cm^2) was then given by the product of the contact resistance (in Ω) and the contact area (in cm^2).

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. Seven samples were tested for each rebar surface condition (as-received or acetone washed). The acetone washing was conducted by immersion of the rebar in acetone for 15 min, followed by drying in air.

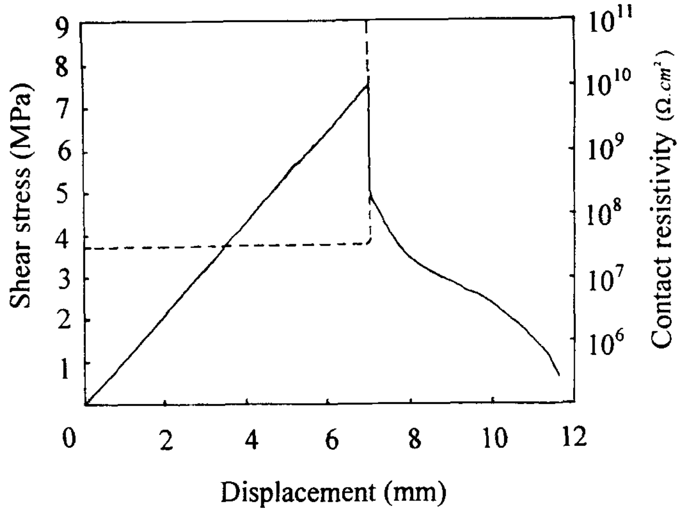

Fig. 2 Plots of shear stress vs. displacement (solid curve) and of contact electrical resistivity vs. displacement (dashed curve) simultaneously obtained during pull-out testing of steel rebar from concrete at 28 days.

Results

Fig. 2 gives a plot of shear stress vs. displacement and a simultaneously obtained plot of contact resistivity vs. displacement for an as-received rebar at 28 days of concrete curing. Corresponding plots for an acetone washed rebar were essentially the same as those for an as-received rebar. 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.

Table 1 gives the embedment length, bond strength and contact electrical resistivity of all samples tested at 28 days. Fig. 3 shows the correlation of the contact resistivity with the bond strength. The contact resistivity increased linearly with increasing bond strength, such that the data for the as-received rebar and those for the acetone washed rebar lie on two essentially parallel straight lines. Acetone washing increased the bond strength slightly and decreased the contact resistivity slightly, probably because of the degreasing action of the acetone.

Discussion

The contact resistivity increases with increasing bond strength for both the bond between stainless steel fiber and cement paste [1,2] and that between mild steel rebar and concrete (this work). The origin of this dependence in associated with interfacial phase(s) of volume resistivity higher than that of cement paste or concrete, as pointed out in Ref. 1. The interfacial phase enhances the bonding. It may be a metal oxide. Acetone washing of the rebar does not affect this interfacial phase, so that the linear relationship is not affected. However, acetone washing removes grease from the surface of the rebar, thus increasing the bond strength slightly and decreasing the contact resistivity slightly. Due to the interfacial phase of high volume resistivity, the contact resistivity does not increase during debonding (Fig. 2).

Table 1. Measured bond strength and contact electrical resistivity.

Embedment length (mm) ± 0.2	Bond strength (MPa)	Contact resistivity (Ω.cm^2)
As-received rebar		
151.2	6.03±0.08	$4.92 \times 10^7 \pm 5.1 \times 10^5$
153.4	6.34±0.20	$5.31 \times 10^7 \pm 6.8 \times 10^5$
152.7	6.57±0.09	$5.55 \times 10^7 \pm 4.2 \times 10^5$
150.8	6.83±0.18	$5.82 \times 10^7 \pm 2.1 \times 10^6$
151.9	7.06±0.22	$6.15 \times 10^7 \pm 7.2 \times 10^5$
153.7	7.34±0.23	$6.34 \times 10^7 \pm 1.2 \times 10^6$
150.2	7.61±0.15	$6.84 \times 10^7 \pm 2.3 \times 10^6$
Acetone washed rebar		
152.8	6.15±0.09	$4.67 \times 10^7 \pm 6.3 \times 10^5$
151.6	6.48±0.23	$5.05 \times 10^7 \pm 7.2 \times 10^5$
153.7	6.69±0.17	$5.34 \times 10^7 \pm 1.2 \times 10^6$
150.9	6.98±0.26	$5.61 \times 10^7 \pm 2.5 \times 10^6$
153.5	7.22±0.25	$5.81 \times 10^7 \pm 6.9 \times 10^5$
150.4	7.46±0.12	$6.24 \times 10^7 \pm 7.8 \times 10^5$
151.8	7.79±0.16	$6.52 \times 10^7 \pm 4.3 \times 10^6$

In the case of the bond between a carbon fiber and cement paste, the contact resistivity decreases with increasing bond strength and increases gradually during debonding [3]. This drastic difference from the steel fiber/rebar case is due to the absence of an oxide film (except for a monolayer) on carbon and the resulting absence of an interfacial phase of high volume resistivity.

The contact resistivity for the bond between steel rebar and concrete (this work) is higher than that between steel fiber and cement paste [1,2]. On the other hand, the bond strength of the former (this work) is higher than that of the latter [1,2]. The difference in bond strength is probably due to the presence of deformations on the steel rebar and the absence of deformations on the steel fiber. The difference in contact resistivity occurs in spite of the deformations, the presence of which increases the effective contact area and thus decreases the measured contact resistivity (which does not take into account the increased area due to the deformations). Therefore, the high contact resistivity for the rebar-concrete case is attributed to the presence of aggregates in the rebar-concrete case and the absence of aggregates in the fiber-cement case, as the aggregates may cause more voids at the interface and voids are electrically insulating.

Although the results of this work are scientifically quite similar to those of Ref. 1 and 2, this work is practically more significant than Ref. 1 and 2, because it provides a practical, quick and nondestructive method for assessing the bond strength between steel rebar and concrete. As no pull-out

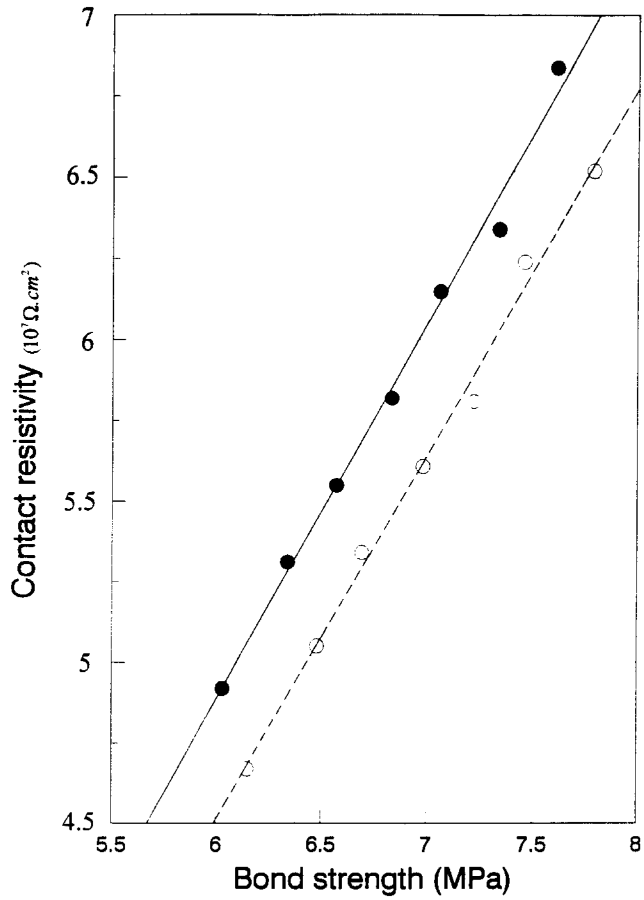

Fig. 3 Variation of contact electrical resistivity with bond strength at 28 days. Solid curve and solid circles : as-received rebar. Dashed curve and open circles : acetone washed rebar.

is required for this assessment and the electronic equipment required is simple, the method can be used in the field on concrete structures containing steel rebars.

Conclusion

The bond strength and contact electrical resistivity between mild steel rebar and concrete were found to be linearly related, as in the previously reported case of the bond between stainless steel fiber and cement paste. This relationship is attributed to an interfacial phase (probably an oxide) of high volume resistivity that helps the bonding. Also because of this interfacial phase, the contact resistivity does not increase during debonding, although it abruptly increases at the end of debonding and the start of pull-out. This correlation between bond strength and contact electrical resisitivity provides a nondestructive method for assessing the bond strength.

Acetone washing of steel rebar does not affect the linear correlation mentioned above, but it increases the bond strength slightly and decreases the contact resistivity slightly, probably due to its degreasing action on the rebar.

References

1. Xuli Fu and D.D.L. Chung, MRS Symp. Proc. Vol. 370 (Microstructure of Cement-Based Systems/Bonding and Interfaces in Cementitious Materials), edited by S. Diamond, S. Mindess, F.P. Glasser, L.W. Roberts, J.P. Skalny and L.D. Wakeley, 1995, p. 559-563.

2. Xuli Fu and D.D.L. Chung, submitted for publication.

3. Xuli Fu and D.D.L. Chung, Cem. Concr. Res., 25 (1995).