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Nondestructive Bond Strength Testing by Contact Electrical Resistivity Measurement

by Xuli Fu and D. D. L. Chung

Synopsis: The contact electrical resistivity was found to correlate with the shear bond strength between steel rebar and concrete, between stainless steel fiber and cement paste, and between carbon fiber and cement paste. For the bond between steel rebar and concrete and that between stainless steel fiber (untreated or acetone washed) and cement paste, the contact resistivity increased linearly with increasing bond strength, due to an interfacial phase of high volume resistivity that helped the bonding. For the bond between stainless steel fiber (acid washed) and cement paste and that between carbon fiber (untreated) and cement paste, the contact resistivity decreased with increasing bond strength, due to the bond degradation by interfacial voids, which were high in volume resistivity. The acid washing of the stainless steel fiber decreased the contact resistivity, but had little effect on the bond strength. The high volume resistivity interfacial phase that enhanced the bonding between the untreated or acetone washed stainless steel fiber and cement paste apparently required for its formation the oxide layer on the stainless steel surface. The removal of the oxide layer by acid washing eliminated this phase, thus decreasing the contact resistivity and causing the contact resistivity to decrease with increasing bond strength. For a given interface at a given curing age, the correlation between bond strength and contact resistivity allows the bond strength to be nondestructively measured via contact resistivity measurement.

Keywords: bond (concrete to reinforcement); carbon; cements; concretes; electrical resistance; fibers; reinforcing steels

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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 directly by pull-out testing (1-6) and indirectly by flexural testing (7). Because both methods destroy the bond, they 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 contact electrical resistivity is defined as the electrical resistivity of an electrical contact (i.e., an interface) in the direction perpendicular to the contact. It is a quantity that does not depend on the interface geometry, but only depends on the physical or chemical nature of the interface. Its unit is $\Omega.cm^2$. It is equal to the contact resistance (in Ω) multiplied by the contact area (in cm^2). In contrast, the contact resistance depends on the geometry. The contact resistivity should be distinguished from the volume resistivity, which is defined as the resistivity of a three-dimensional material in a particular direction. The volume resistivity is also independent of the geometry. Its unit is Ω.cm; it is equal to the volume resistance (in Ω) multiplied by the cross-sectional area perpendicular to the direction of interest and divided by the length in the direction of interest. The volume resistance depends on the geometry. Previous workers have measured either the volume resistivity or the volume resistance of steel rebars (8), mortars (9) and cement pastes (10-12), but have not measured the contact resistivity of any interface that is relevant to the field of concrete.

A nondestructive method that provides an indirect measurement of the bond strength is provided in this paper. This method involves measurement of the contact electrical resistivity between steel (or, in general, an electrically conducting reinforcement) and the cementitious material. Good correlation was found between bond strength and contact electrical resistivity for a given interface (i.e., steel rebar in contact with concrete, stainless steel fiber having had a given surface treatment in contact with cement paste, or carbon fiber in contact with cement paste) and a given curing age. This correlation not only provides a non-destructive testing method, it also provides information on the structure of the interface.

BOND BETWEEN STEEL REBAR AND CONCRETE

This section applies the nondestructive method of this paper to studying the bond between steel rebar and concrete.

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 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% (room humidity). 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 applied 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 was then given by the product of the contact resistance and the contact area.

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 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.

BOND BETWEEN STAINLESS STEEL FIBER AND CEMENT PASTE

This section applies the nondestructive method of this paper to studying the bond between stainless steel fiber and cement paste.

Stainless steel (Fe-Cr-Al) fibers described in Table 2 were used for the steel material. The as-received fibers were subjected to two different surface treatments, namely acetone (reagent grade) washing and acid (37.71% hydrychloric acid, reagent grade) washing. The washing was conducted by stirring the fibers in a beaker containing either acetone or acid for 5-10 min. For the case of acetone washing, washing was followed by air drying at room temperature for 10-15 min. For the case of acid washing, washing was followed by rinsing in water and then air oven drying at 200°C for 5-10 min.

Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. The water reducing agent used in the amount of 0.5% by weight of cement was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93-96% sodium salt of a condensed naphthalenesulfonic acid. The volume electrical resistivity of the cement paste was 1.40×10^5, 1.53×10^5, 1.58×10^5 and 1.62×10^5 Ω.cm at 1, 7, 14 and 28 days of curing respectively, as measured by the four-probe method using silver paint for electrical contacts.

The contact electrical resistivity between the fiber and the cement paste was measured at 1, 7, 14 and 28 days of curing using the four-probe method and silver paint as electrical contacts, as illustrated in Fig. 4. One current contact and one voltage contact were on the fiber, while the other voltage and current contacts were on the cement paste embedding the fiber to a distance of 1 cm. The cement paste thickness was 1.5 mm on each side sandwiching the fiber. The fiber length was 5 cm. 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 fiber volume resistance, the interface contact resistance and the cement paste volume resistance. The measured resistance turned out to be dominated by the contact resistance, to the extent that the two volume resistance terms can be neglected.

Single fiber pull-out testing was conducted on the same interface samples and at the same time as the contact resistivity was measured. For pull-out testing, one end of the fiber was embedded in cement paste, as in Fig. 4. A Sintech 2/D screw-action mechanical testing system was used. 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 interface samples were tested for each combination of fiber surface treatment (as-received, acetone washed or acid washed) and curing time (1, 7, 14 or 28 days).

Scanning electron microscopy was performed on the as-received, acetone washed and acid washed fibers in order to investigate the effect of surface treatment on the surface morphology.

Weight measurements were conducted on the fibers both before and after acetone washing and before and after acid washing in order to investigate the effect of surface treatment on the weight. The washing process included the drying step. Six specimens were used for each type of washing.

Fig. 5-7 give typical plots of shear stress vs. displacement and simultaneously obtained plots of contact electrical resistivity vs. displacement for as-received, acetone washed and acid washed fibers respectively at 28 days of curing. In all three cases, the contact resistivity abruptly increased when the shear stress reached its maximum, i.e., when fiber-matrix debonding was completed. For the as-received and acetone washed fibers (Fig. 5 and 6), the contact resistivity did not change before the abrupt increase when the shear stress had reached its maximum. For the acid washed fibers (Fig. 7), the contact resistivity gradually increased prior to the abrupt increase when the shear stress had reached its maximum.

Fig. 8 shows the correlation of the contact resistivity with the bond strength at 28 days for the as-received, acetone washed and acid washed fibers. For each type of surface treatment, the bond strength as well as contact resistivity varied among the seven samples (identically prepared) tested. Nevertheless, the contact resistivity correlated strongly with the bond strength among the data for each type of surface treatment. For the as-received and acetone washed fibers, the contact resistivity increased with increasing bond strength. For the case of acid washed fibers, the contact resistivity decreased with increasing bond strength. The range of bond strength was similar for the three types of surface treatment, but the range of contact resistivity was lower for the acid washed case than the as-received and acetone washed cases.

Fig. 9-11 show the dependence of the bond strength and contact resistivity on the curing age for as-received, acetone washed and acid washed fibers respectively. The bond strength decreased while the contact resistivity increased with curing age (particularly from 1 to 14 days) for both as-recieved and acetone washed cases (Fig. 9 and 10); at each curing age, the contact resistivity increased roughly linearly with increasing bond strength, such that negative deviation from linearity occurred in the high bond strength regime. For the acid washed case (Fig. 11), the contact resistivity decreased in a non-linear fashion with increasing bond strength; due to the non-linearity, the dependence of the bond strength and contact resistivity on the curing age could not be determined.

As shown by scanning electron microscopy, acetone washing slightly roughened the surface, whereas acid washing significantly roughened the surface. The fractional weight loss due to acetone washing was $(2.9 \pm 0.5)\%$ and that due to acid washing was $(20.4 \pm 1.2)\%$.

BOND BETWEEN CARBON FIBER AND CEMENT PASTE

This section applies the nondestructive method of this paper to studying the bond between carbon fiber and cement paste.

The carbon fibers were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, Kentucky). The fiber properties are shown in Table 3. Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. The water reducing agent used in the amount of 0.5% by weight of cement was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93-96% sodium salt of a condensed naphthalenesulfonic acid. The volume electrical resistivity of the cement paste was 1.62×10^5 Ω.cm at 28 days of curing, as measured by the four-probe method using silver paint for electrical contacts.

The contact electrical resistivity between the fiber and the cement paste was measured at 28 days of curing using the four-probe method and silver paint as electrical contacts, as illustrated in Fig. 4. One current contact and one voltage contact were on the fiber, while the other voltage and current contacts were on the cement paste embedding the fiber to a distance ranging from 0.51 to 1.50 mm, as measured for each sample tested. The cement paste thickness was 1 mm on each side sandwiching the fiber. The fiber length was 1 cm. The current was 0.5-2.0 A; the voltage was 3-4 V. The resistance between the two voltage probes was measured; it corresponds to the sum of the fiber volume resistance, the interface contact resistance and the cement paste volume resistance. The measured resistance turned out to be dominated by the contact resistance, to the extent that the two volume resistance terms can be neglected.

Single fiber pull-out testing was conducted as described above for stainless steel fiber. Nine interface samples were tested. Fig. 12 gives a typical plot of shear stress vs. displacement and the simultaneously obtained plot of contact resistivity vs. displacement at 28 days of curing. The contact resistivity gradually increased prior to the abrupt increase when the shear stress had reached its maximum. Fig. 13 shows the correlation of the contact resistivity with the bond strength for the nine samples. The contact resistivity decreased with increasing bond strength.

DISCUSSION

The contact resistivity increases with increasing bond strength for both the bond between stainless steel fiber (untreated or acteone washed) and cement paste and that between mild steel rebar and concrete. The origin of this dependence is associated with interfacial phase(s) of volume resistivity higher than that of cement paste or concrete. 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, 5 and 6). On the other hand, acid washing removes phase(s) (probably metal oxides and other compounds) from the surface of the fibers, as suggested by the roughening of the surface and the 20% weight loss. The removal of the phase(s) by acid washing apparently makes it impossible for the high resistivity phase(s) that enhance the bonding to form when the fiber subsequently encounters the cement paste. As a result, the interfacial voids govern the bond strength, so the contact resistivity increases as the interfacial void content increases during debonding (Fig. 7). That the bond strength decreases and the contact resistivity increases with curing age (Fig. 9-11) suggests that, as curing occurs, the interfacial void content increases, probably due to drying shrinkage of the cement paste.

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. 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 is higher than that between steel fiber and cement paste. On the other hand, the bond strength of the former is higher than that of the latter. 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, whether they are filled with a liquid or not.

CONCLUSION

The bond strength and contact electrical resistivity between mild steel rebar and concrete were found to be linearly related, as in the case of the bond between stainless steel fiber (untreated or acetone washed) 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 resistivity 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.

For acid washed stainless steel fiber and carbon fiber, the contact resistivity decreased with increasing bond strength, because the interfacial voids caused the resistivity to increase and the bond strength to decrease; the contact resistivity was lower than for as-received or acetone washed stainless steel fibers.

The bond strength decreased and the contact resistivity increased with increasing curing age for as-received and acetone washed stainless steel fibers, due to interfacial void content increase.

For both steel rebar and stainless steel fiber, acetone washing increased the bond strength and decreased the contact resistivity.

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TABLE 1 — MEASURED BOND STRENGTH AND CONTACT ELECTRICAL RESISTIVITY

Embedment length (mm) ± 0.2	Bond strength (MPa)	Contact resistivity ($\Omega.cm^2$)
As-received rebar		
151.2	6.03±0.08	$4.92x10^7 \pm 5.1x10^5$
153.4	6.34±0.20	$5.31x10^7 \pm 6.8x10^5$
152.7	6.57±0.09	$5.55x10^7 \pm 4.2x10^5$
150.8	6.83±0.18	$5.82x10^7 \pm 2.1x10^6$
151.9	7.06±0.22	$6.15x10^7 \pm 7.2x10^5$
153.7	7.34±0.23	$6.34x10^7 \pm 1.2x10^6$
150.2	7.61±0.15	$6.84x10^7 \pm 2.3x10^6$
Acetone washed rebar		
152.8	6.15±0.09	$4.67x10^7 \pm 6.3x10^5$
151.6	6.48±0.23	$5.05x10^7 \pm 7.2x10^5$
153.7	6.69±0.17	$5.34x10^7 \pm 1.2x10^6$
150.9	6.98±0.26	$5.61x10^7 \pm 2.5x10^6$
153.5	7.22±0.25	$5.81x10^7 \pm 6.9x10^5$
150.4	7.46±0.12	$6.24x10^7 \pm 7.8x10^5$
151.8	7.79±0.16	$6.52x10^7 \pm 4.3x10^6$

TABLE 2 — PROPERTIES OF STEEL FIBERS

Type of steel	Stainless 434
Manufacturer	International Steel Wool Corp. (Springfield, OH)
Length	5 mm
Diameter	60 µm
Density	7.7 $g.cm^3$
Modulus	200 GPa (2.9 x 10^7 psi)
Elongation at break	3.2%
Tensile strength	970 MPa (1.4 x 10^5 psi)
Volume electrical resistivity	6 x 10^{-5} Ω.cm

TABLE 3 — PROPERTIES OF CARBON FIBERS

Filament diameter	10 µm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	3.0 x 10^{-3} Ω.cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt.%

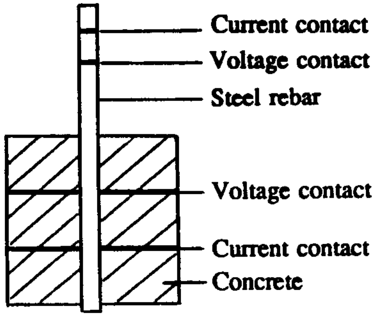


Fig. 1—Sample configuration for measuring contact electrical resistivity and shear bond strength between steel reinforcing bar and concrete

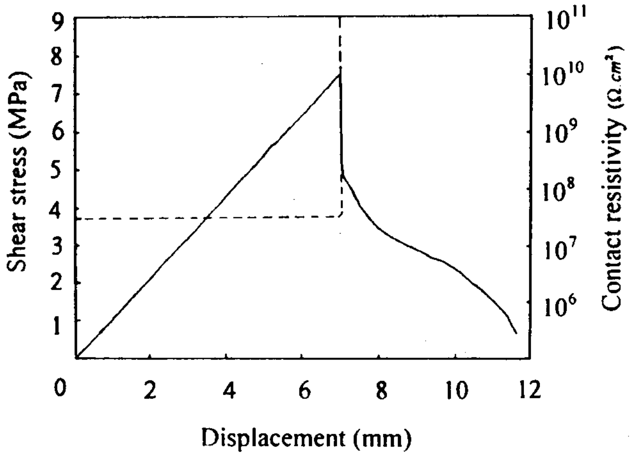


Fig. 2—Plots of shear stress versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pullout testing of steel reinforcing bar from concrete at 28 days

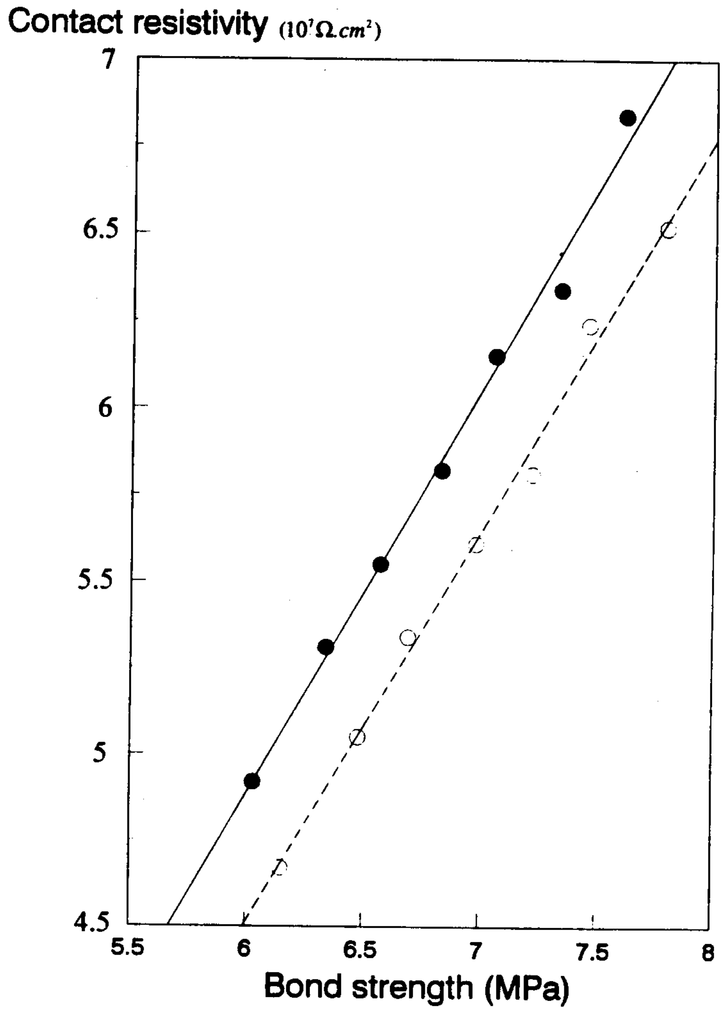


Fig. 3—Variation of contact electrical resistivity with bond strength between steel reinforcing bar and concrete at 28 days. Solid curve and solid circle: as-received reinforcing bar. Dashed curve and open circles: acetone-washed bar.

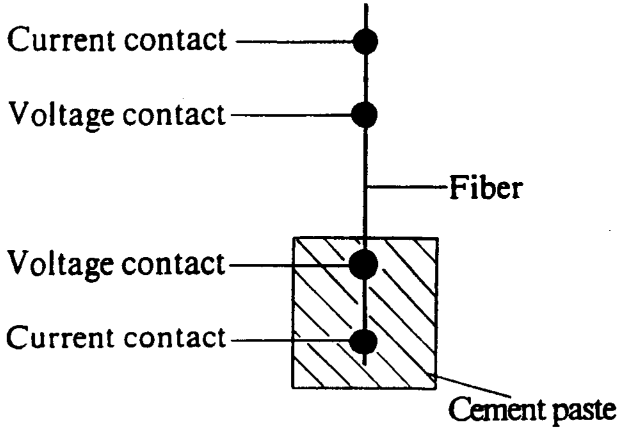


Fig. 4—Sample configuration for measuring contact electrical resistivity of interface between fiber and cement paste

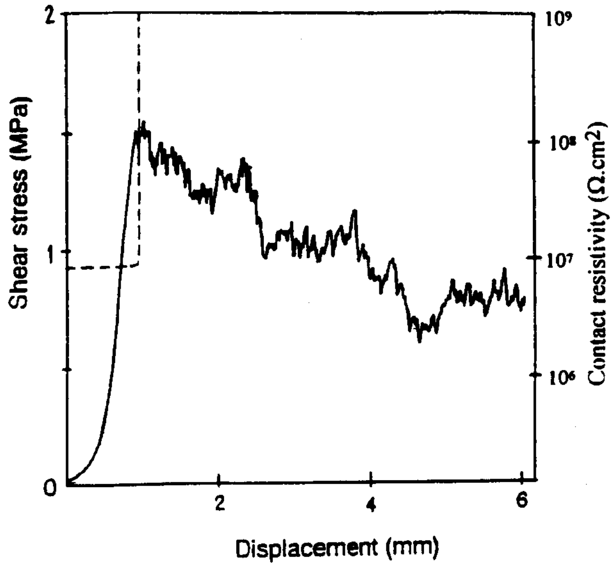


Fig. 5—Plots of shear stress versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pullout testing of as-received stainless steel fiber from cement past at 28 days of curing

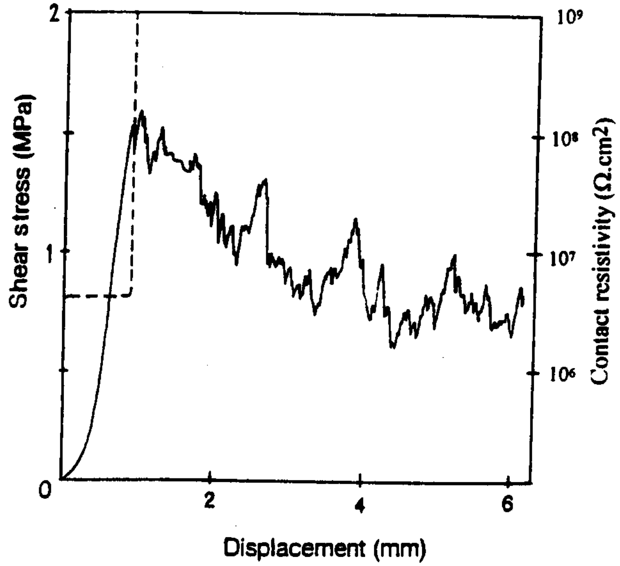


Fig. 6—Plots of shear stress versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pullout testing of acetone-washed stainless steel fiber from cement paste at 28 days of curing

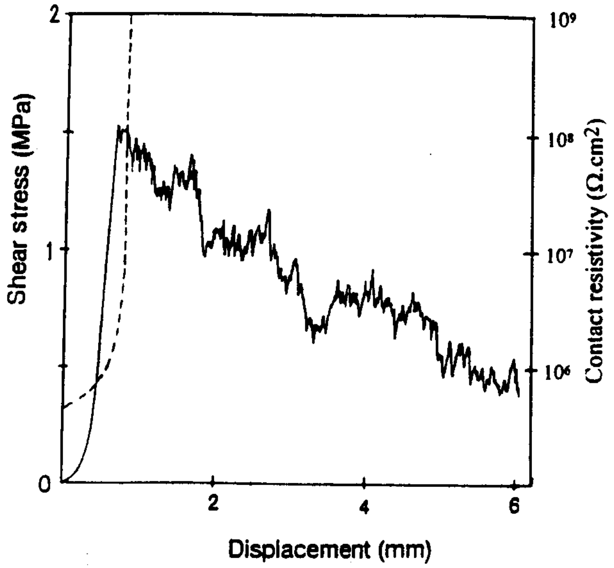
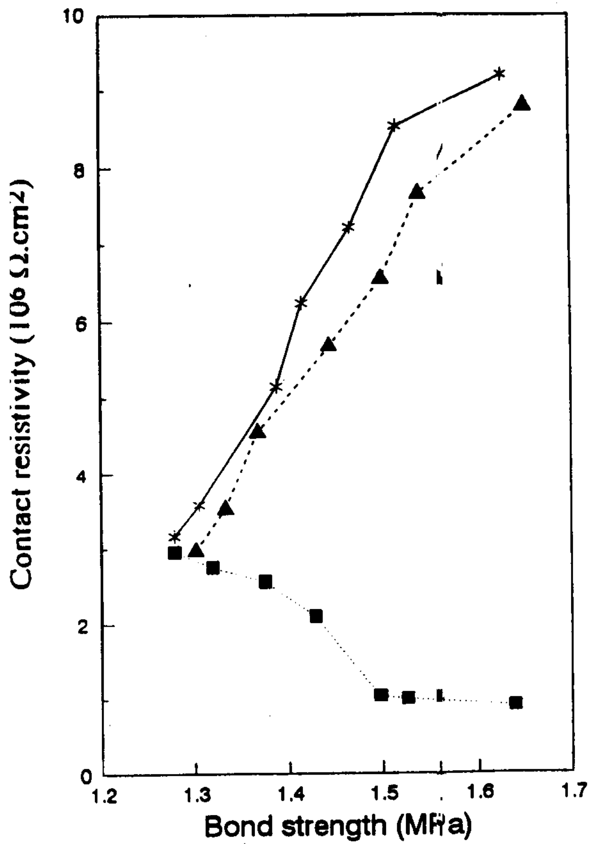


Fig. 7—Plots of shear stress versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pullout testing of acid-washed stainless steel fiber from cement paste at 28 days of curing



—Vari—tion of contact electrical resistivity with bond strength between ess sesel fiber and cement paste at 28 days of curing for as-received), ace), ne-washed (triangles), and acid-washed (squares) stainless steel

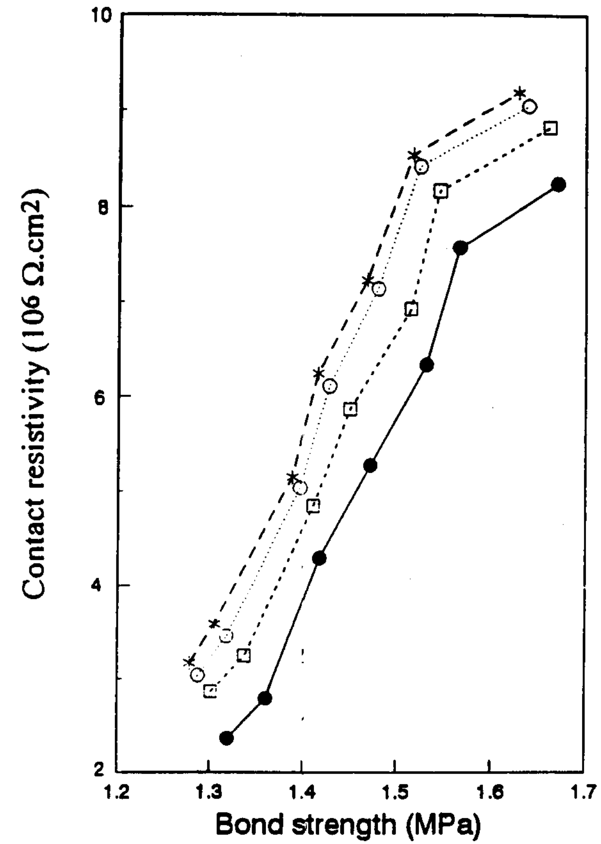


Fig. 9—Variation of contact electrical resistivity with bond strength between stainless steel fiber and cement paste for as-received stainless steel fibers at 1 (solid circles), 7 (squares), 14 (open circles), and 28 (stars) days of curing

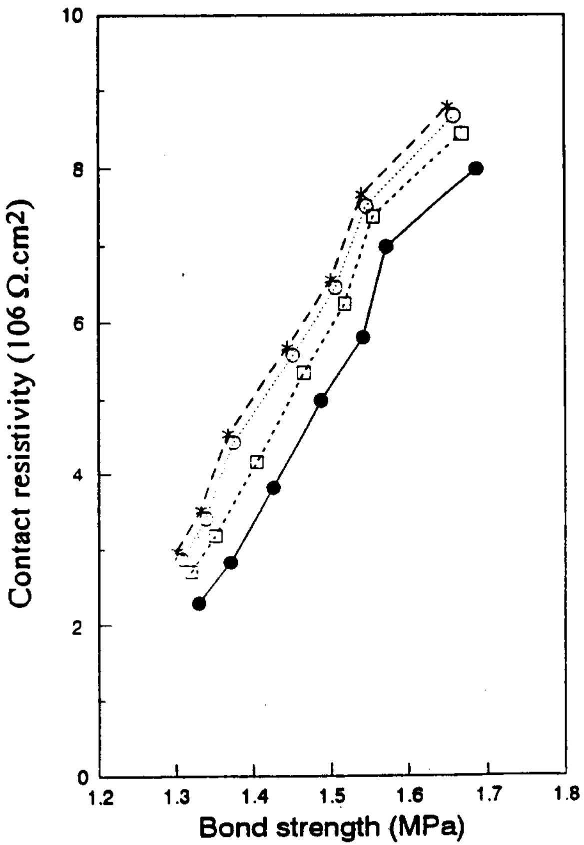


Fig. 10—Variation of contact electrical resistivity with bond strength between stainless steel fiber and cement paste for acetone-washed stainless steel fibers at 1 (solid circles), 7 (squares), 14 (open circles), and 28 (stars) days of curing

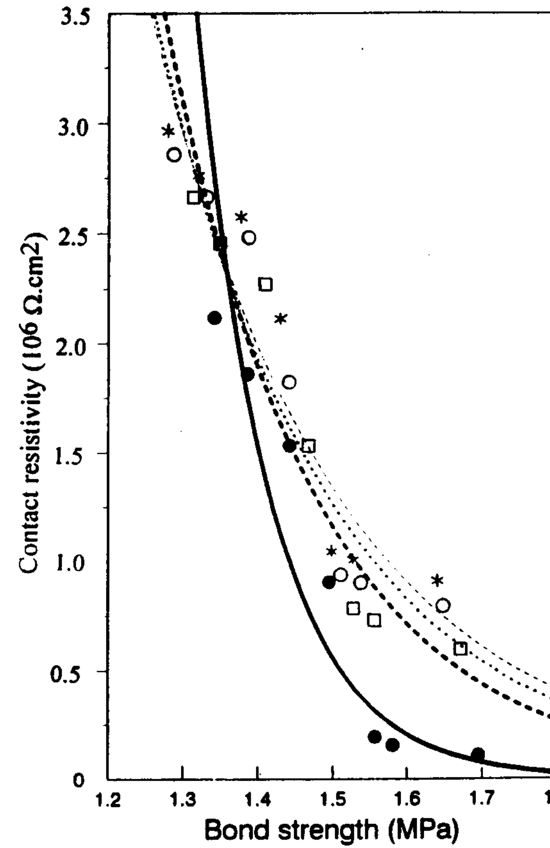


Fig. 11—Variation of contact electrical resistivity with bond strength between stainless steel fiber and cement paste for acid-washed stainless steel fibers at 1 (solid circles), 7 (squares), 14 (open circles), and 28 (stars) days of curing

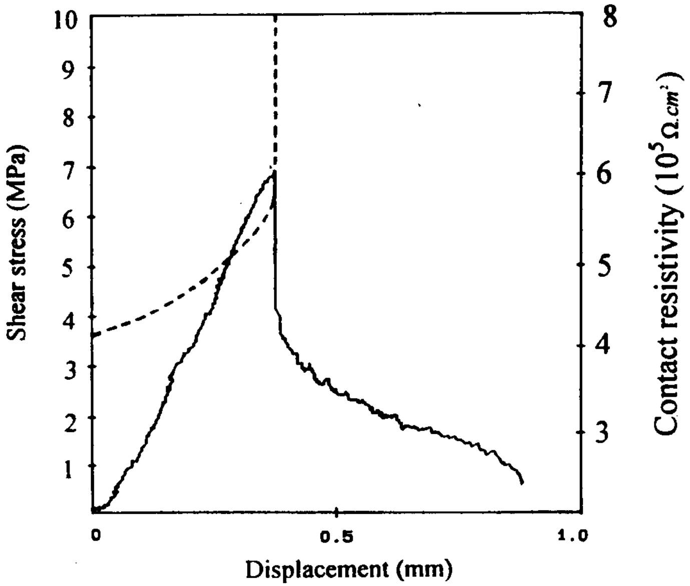


Fig. 12—Plots of shear stress versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pullout testing of carbon fiber from cement paste at 28 days of curing

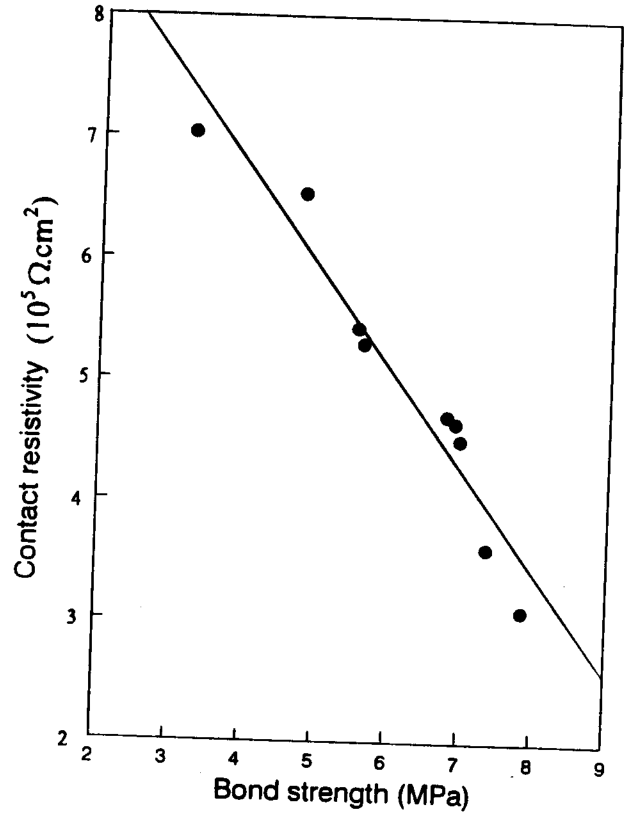


Fig. 13—Variation of contact electrical resistivity with bond strength between carbon fiber and cement paste at 28 days of curing