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Improving the Bond Strength of Concrete to Reinforcement by Adding Methylcellulose to Concrete


by Xuli Fu and D. D. L. Chung

The use of methylcellulose (0.4 to 0.8 percent by weight of cement) as an admixture in cement paste or concrete was found to increase the shear bond strength with steel reinforcing bar, steel fiber or carbon fiber to values attained by using latex (20 percent by weight of cement) as an admixture, even though latex was used in a much larger quantity than methylcellulose. The bond strength increased with increasing methylcellulose amount. The contact electrical resistivity between cement and fiber or between concrete and reinforcing bar was increased by latex addition, but not changed by methylcellulose addition. The combined use of silica fume (15 percent by weight of cement) and methylcellulose (0.4 percent by weight of cement) as admixtures was found to give concrete that exhibited high bond strength to steel reinforcing bar, in addition to previously reported high tensile modulus, tensile ductility, flexural strength and flexural toughness; the bond strength attained was higher than that attained by using either silica fume or methylcellulose as admixture. Latex in combination with silica fume did not work due to low workability. Methylcellulose in combination with silica fume was effective due to silica fume increasing the matrix modulus and methylcellulose promoting adhesion.

Keywords: bond strength; carbon; cement; concrete; electrical resistivity; fiber; latex; methylcellulose; silica fume; steel.

INTRODUCTION

The bond of concrete to steel reinforcing bars and other reinforcements is important, since concrete is usually reinforced and the reinforcement often tends to carry the load. The bond strength between concrete and reinforcement depends much on the concrete mix design, although it also depends on the reinforcement surface condition. The addition of latex to the concrete/mortar mix is known to increase the bond strength between cement and aggregate, between cement and reinforcement, and between old mortar and new mortar,[1-9] due to the latex interfacial layer.[6,10,11] The addition of cellulose derivatives also helps these three types of bond,[9,12,13] but much less attention has been given to the cellulose derivatives than latex. The amount of latex required is high, say, 20 percent by weight of cement. Consequently, the cost of the latex addition is high. This paper describes the use of methylcellulose (a cellulose derivative) in a small amount, as little as 0.4 percent by weight of cement, for increasing the bond strength between cement and reinforcement. The reinforcements included in this study are mild steel reinforcing bar, stainless steel fiber and carbon fiber. The effects of methylcellulose addition on the adhesion to these reinforcements have been previously reported in separate publications.[14-16] This paper is aimed at providing a coherent view of these effects in terms of both bond strength and contact electrical resistivity (related to the interface structure, such as the interfacial void content and the interfacial phase[s]).[17] The interfaces addressed are that between concrete and mild steel reinforcing bar, that between cement paste and stainless steel fiber and that between cement paste and carbon fiber. In each case, a comparison is made between methylcellulose addition and latex addition.

Cellulose derivatives are used as antiwashout admixtures in underwater concrete.[12,18-20] They also increase the bond strength between concrete and steel reinforcing bar in the top position, due to reduced bleeding, settlement and segregation associated with increased cohesiveness.[12] Methylcellulose addition is known to increase the tensile strength, tensile ductility and flexural storage modulus, as shown for cement pastes.[21-23] The effects of methylcellulose (0.4 percent by weight of cement) on the tensile strength and ductility are less than those of latex (20 percent by weight of cement),[22] but the effect of methylcellulose (0.4 percent by weight of cement) on the flexural storage modulus is more than that of latex (20 percent by weight of cement).[23] Methylcellulose addition (0.4 percent by weight of cement) increases the air void content, whereas latex addition (20 percent by weight of cement) decreases it, as shown for cement pastes.[22] The average air void size is larger for methylcellulose addition than latex addition.[22] Both methylcellulose and latex additions decrease the thermal stability and the apparent coefficient of thermal expansion.[15,19]

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RESEARCH SIGNIFICANCE

This paper provides a comparative study of two polymer admixtures, namely methylcellulose (0.4 to 0.8 percent by weight of cement, with and without silica fume in the amount of 15 percent by weight of cement) and latex (20 percent by weight of cement), in their ability to increase the bond strength between concrete and reinforcement (steel reinforcing bar, steel fiber and carbon fiber).

EXPERIMENTAL METHODS

Cement paste made from Type I portland cement was used for the cementitious material. Three types of cement pastes were used, namely (1) plain cement paste (with only cement and water, such that the water-cement ratio is 0.45), (2) cement paste with methylcellulose in the amount of 0.4 percent by weight of cement (together with water reducing agent in the amount of 1 percent by weight of cement, and with water-cement ratio = 0.32), and (3) cement paste with latex in the amount of 20 percent by weight of cement (water-cement ratio = 0.23, without water reducing agent). The water reducing agent used in cement paste (2) contained 93 to 96 percent sodium salt of a condensed naphthalenesulfonic acid. The amounts of water and water reducing agent relative to cement for each paste were chosen in order to maintain the slump at around 170 mm. Methylcellulose in the amount of 0.4 percent of the cement weight was used in cement paste (2). The defoamer used along with it was in the amount of 0.13 vol. percent; it was used whenever methylcellulose was used. The latex used in cement paste (3) was a styrene-butadiene polymer in a dispersion with 48 percent solid; the dispersion was used in the amount of 20 percent by weight of cement. The antifoam used was in the amount of 0.5 percent by weight of latex; it was used whenever latex was used. A mixer with a flat beater was used for mixing. For the case of cement paste containing latex, the latex and antifoam first were mixed by hand for about 1 min. Then this mixture, cement, water and the water reducing agent were mixed in the mixer for 5 min. For the case of cement paste containing methylcellulose, methylcellulose was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Then this mixture, cement, water and water reducing agent were mixed in the Hobart mixer for 5 min. After pouring the mix into oiled molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air for 28 days.

The concrete was made with Type I portland cement, fine aggregate (natural sand, all of which passed through a No. 4 U.S. sieve) and coarse aggregate (all of which passed through 1 in sieve) in the weight ratio 1:1.5:2.49. The water-cement ratio was 0.45. A water reducing agent (sodium salt of a condensed naphthalenesulfonic acid) was used in the amount of 2 percent by weight of cement. Five types of concrete were used with the above mentioned amounts of water and water reducing agent relative to cement, namely (1) plain concrete, (2) concrete with methylcellulose, (3) concrete with latex, (4) concrete with silica fume, and (5) concrete with silica fume and methylcellulose. Methylcellulose in amounts of 0.4, 0.6, and 0.8 percent by weight of cement was used in concrete (2). Methylcellulose in the amount of 0.4 percent by weight of cement was used in concrete (5). The defoamer used along with methylcellulose was in the amount of 0.13 vol. percent; it was used whenever methylcellulose was used. The latex used in concrete (3) was a styrene-butadiene copolymer; it was used in the amount of 20 percent by weight of cement. The antifoam used was in the amount of 0.5 percent by weight of the latex; it was used whenever latex was used. Silica fume used in concretes (4) and (5) was in the amount of 15 percent by weight of cement.

All ingredients were mixed in a stone concrete mixer for 15 to 20 minutes. Then the concrete mix was poured into a 6 x 6 x 6 in. (152 x 152 x 152 mm) mold, while a steel reinforcing bar 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 reinforcing bar was No. 6 (19 mm diameter), 260 mm length, and had 90-degree crossed spiral surface deformations of 26 mm pitch and 1 mm protruded height. 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 percent. Steel pull-out testing was carried out according to ASTM C 234 at 28 days of curing. A hydraulic material testing system was used at a crosshead speed of 1.27 mm/min.

The volume electrical resistivity of each concrete at 28 days was 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 values are 1.53×10^7 Ω.cm for concrete (1), 1.55×10^7, 1.58×10^7 and 1.63×10^7 Ω.cm for concrete (2) with methylcellulose in amounts of 0.4, 0.6, and 0.8 percent by weight of cement respectively, 2.77×10^7 Ω.cm for concrete (3), and 2.37×10^7 Ω.cm for concrete (5). Since methylcellulose (0.4 percent by weight of cement) had negligible effect on the resistivity, the resistivities of concretes (4) and (5) were assumed to be the same.

The contact electrical resistivity between the steel reinforcing bar 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 reinforcing bar. The other voltage and current contacts were on the concrete embedding the reinforcing bar, such that each of these contacts was around the whole perimeter of the concrete in a plane perpendicular to the reinforcing bar; the voltage contact was in a plane about 2 in. (51 mm) from the top surface of the concrete, while the current contact was in a plane about 4 in. (102 mm) from the top surface of the concrete. The resistance between the two voltage probes was measured; it corresponds to the sum of the reinforcing bar

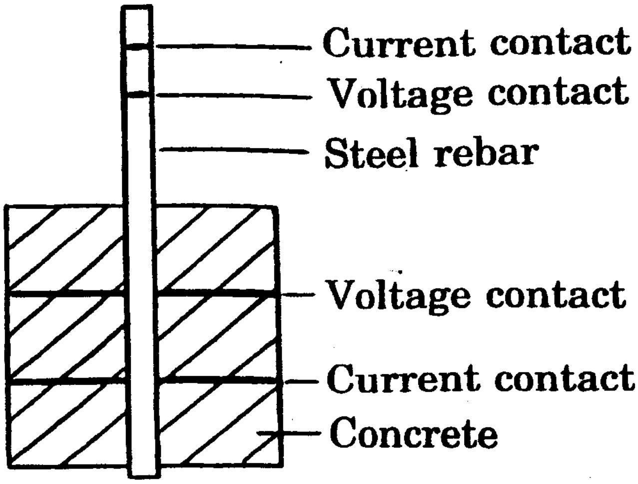

Fig. 1—Sample configuration for measuring the shear bond strength and contact electrical resistivity between steel reinforcing bar and concrete.

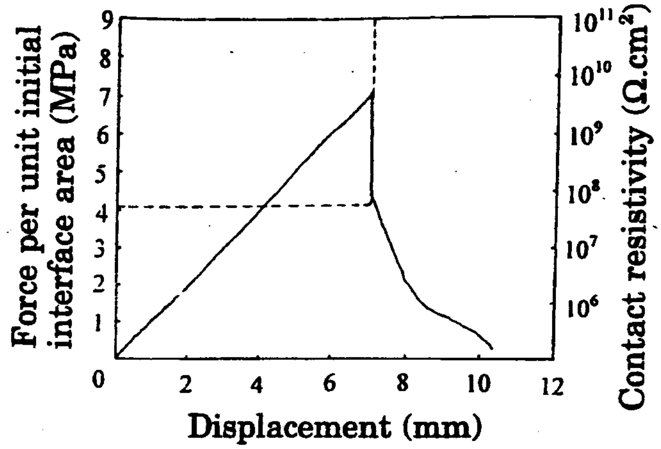

Fig. 2—Plots of force per unit initial interface area versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pull-out testing of acetone-washed steel reinforcing bar from plain concrete.

volume resistance (the resistance down the length of the reinforcing bar), 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 reinforcing bar 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 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 reinforcing bar 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 force during pull-out testing divided by the initial interface area. Fig. 2 gives typical plots of force versus displacement and of contact resistivity versus displacement. At least seven samples were tested for each interface condition.

Stainless steel (Fe-Cr-Al) fibers described in Table 1 were used. The as-received fibers were washed in acetone (reagent grade) by stirring the fibers in a beaker containing acetone for 5 to 10 minutes. Washing was followed by air drying at room temperature for 10 to 15 minutes.

The carbon fibers were isotropic, pitch based and unsized. The fiber properties are shown in Table 2.

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. 1 of Reference 9. 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 which was measured for each specimen. 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. 1, except that the fiber, which replaced the reinforcing bar, protruded only at the top end of the cement paste, which replaced the concrete. A screw-action mechanical testing system was used.

RESULTS

Steel reinforcing bar and concrete

Fig. 2 gives plots of force per unit initial interface area versus displacement and of contact resistivity versus displacement for the case of steel reinforcing bar (acetone washed and then dried at room temperature) and plain concrete. Similar plots were obtained for the concrete with methylcellulose (with or without silica fume), the concrete with latex and as-received steel reinforcing bar. The contact resistivity abruptly increased when the force reached its maximum (i.e., when the steel-concrete debonding was completed). It did not change before this abrupt increase.

Fig. 3 and 4 show the correlation of the contact resistivity with the shear bond strength. The contact resistivity increased roughly linearly with increasing bond strength, such that the data for the different concretes lies on essentially parallel straight lines. The roughly linear relationship in each case is due to the presence of an interfacial phase of high volume resistivity that helped the bonding. The phase is probably an iron oxide. The greater is the amount of this phase, the higher is the bond strength and the higher is the contact electrical resistivity. Fig. 3 shows that methylcellulose (0.4 percent by weight of cement) increased the bond strength more than silica fume, while methylcellulose (0.4 percent by weight of cement) in combination with silica fume gave higher bond strength than either silica fume or methylcellulose alone. Silica fume caused a slight increase in contact resistivity, indicating no decrease of the interfacial void content. This means that the bond strength increase due to silica fume addition is not due to decrease of the interfacial

Table 1—Properties of steel fibers

Type of steel	Stainless 434
Length	5 mm
Diameter	60 μm
Density	7.7 $g.cm^{-3}$
Modulus	200 GPa (2.9×10^7 psi)
Elongation at break	3.2 percent
Tensile strength	970 MPa (1.4×10^5 psi)
Volume electrical resistivity	6×10^{-5} Ωcm

Table 2—Properties of carbon fibers

Filament diameter	15 ± 3 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4 percent
Electrical resistivity	3.0×10^{-3} Ωcm
Specific gravity	1.6 $g.cm^{-3}$
Carbon content	98 weight, percent

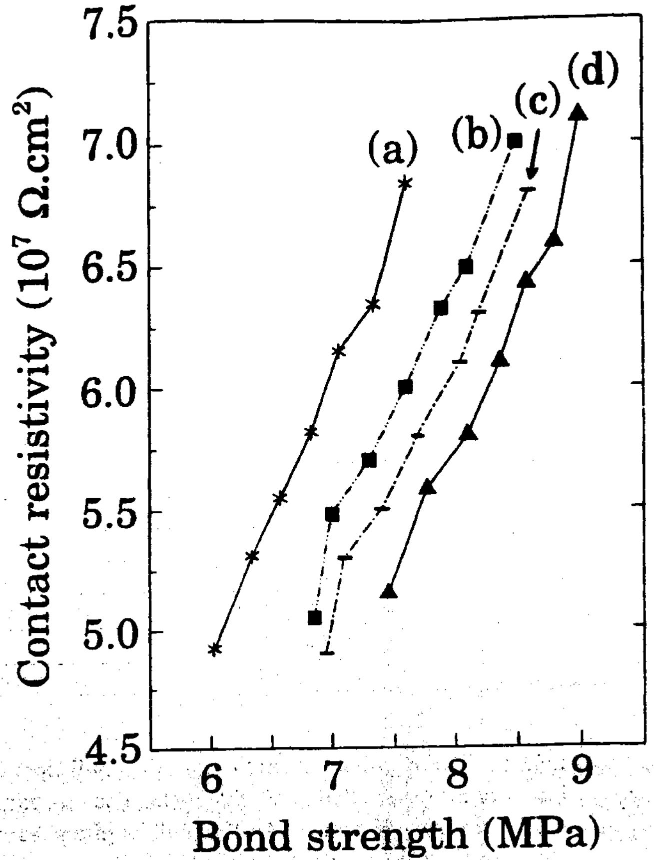

Fig. 3—Variation of contact electrical resistivity with shear bond strength. (a) Plain concrete. (b) Concrete with silica fume. (c) Concrete with methylcellulose (0.4 percent by weight of cement). (d) Concrete with silica fume and methylcellulose (0.4 percent by weight of cement).

void content. Fig. 4 shows that methylcellulose (0.8 percent by weight of cement) gave essentially the same bond strength as methylcellulose (0.4 percent by weight of cement) in combination with silica fume, and also essentially the same bond strength as latex (20 percent by weight of cement). The bond strength increased monotonically with increasing methylcellulose amount (from 0.4 to 0.6, and to 0.8 percent by weight of cement), although the data for methylcellulose in the amount of 0.6 percent by weight of cement are not shown in Fig. 3 or 4.

The contact resistivity increase after latex addition is presumably due to the high volume resistivity of the latex at the reinforcing bar-concrete interface. The bond strength increase after latex or methylcellulose addition is attributed to the adhesion provided by the polymer at the interface. The effectiveness of silica fume in combination with methylcellulose as admixtures is due to the combined effect in which silica fume causes matrix modulus increase (rather than interfacial void content decrease, Table 3) while methylcellulose improves adhesion.

Steel fiber and cement paste

Fig. 5 gives plots of shear stress versus displacement and of contact resistivity versus displacement for the case of steel fiber (acetone washed and then dried at room temperature) and cement paste with methylcellulose. Similar plots were obtained for plain cement paste and cement paste with latex. As in the case of steel reinforcing bar and concrete (Fig. 2), the contact resistivity abruptly increased when the force reached its maximum, i.e., when fiber-matrix debonding was completed. It did not change before the abrupt increase when the force had reached its maximum.

Fig. 6 shows the correlation of the contact resistivity with the bond strength. The contact resistivity increased linearly with the bond strength among the data for each type of cement paste. The bond strength was lower for the plain cement paste than the cement paste with methylcellulose and the cement paste with latex. On the average, the paste with latex gave slightly higher bond strength than that with methylcellulose, but the difference was small. On the average, the contact resistivity was higher for the cement paste with latex than the other two pastes, which were similar in contact resistivity. The linear correlation of the bond strength with the contact electrical resistivity for a given cement paste composition (Fig. 6) and the constancy of the contact resistivity during debonding (Fig. 5) are similar to those reported for the interface between steel reinforcing bar and concrete.

Whether the polymer is latex (20 percent by weight of cement) or methylcellulose (0.4 percent by weight of cement), polymer admixtures to the cementitious matrix help the bond between fiber and matrix. In spite of the large difference in concentration between latex and methylcellulose, the effect on the bond strength is similar. On the other hand, methylcellulose addition does not alter the contact electrical resistivity between fiber and matrix, whereas latex addition increases this resistivity. This suggests that the contact resistivity is less sensitive to a small amount of polymer addition than the bond strength is. For the purpose of cost saving and a low contact resistivity, methylcellulose is preferred to latex as an admixture to the cementitious matrix.

Carbon fiber and cement paste

Fig. 7 gives plots of shear stress versus displacement and of contact resistivity versus displacement for the case of carbon fiber and plain cement paste. The contact resistivity gradually increased prior to the abrupt increase when the shear stress had reached its maximum. The stress also gradually increased as debonding took place and reached its maximum when the fiber-matrix debonding was completed. In other words, the contact resistivity increased as debonding took place. This behavior is in contrast to that for steel reinforcing bar or steel fiber (Fig. 2 and 5).

Fig. 8 shows the correlation of the contact resistivity with the bond strength. The contact resistivity decreased with increasing bond strength for each type of cement paste. Among the samples in each case, a high bond strength is associated with a low contact resistivity, because a high bond strength is associated with a low content of interfacial voids, which are electrically insulating.

For steel fibers and reinforcing bars, the contact electrical resistivity increases with increasing bond strength. However, for carbon fibers, the contact resistivity decreases with increasing bond strength. This difference is attributed to the presence of an oxide film on steel and the absence of an oxide film (except for a monolayer) on carbon. The oxide film on steel helps the bonding, but its high volume electrical resistivity causes the contact resistivity to increase. For carbon fibers, poor bonding is associated with a large void content at the interface. The voids are electrically insulating, so they cause the contact resistivity to be high.

Fig. 8 shows the effect of polymer admixtures (methylcellulose and latex) on the bond between carbon fiber and cement. Either admixture increased both bond strength and contact resistivity. The latter is because the polymers are less conducting than cement. The former is because the polymers improve the adhesion between fiber and cement. Latex and methylcellulose gave similar bond strength increases, but latex caused the contact resistivity to increase, whereas methylcellulose did not.

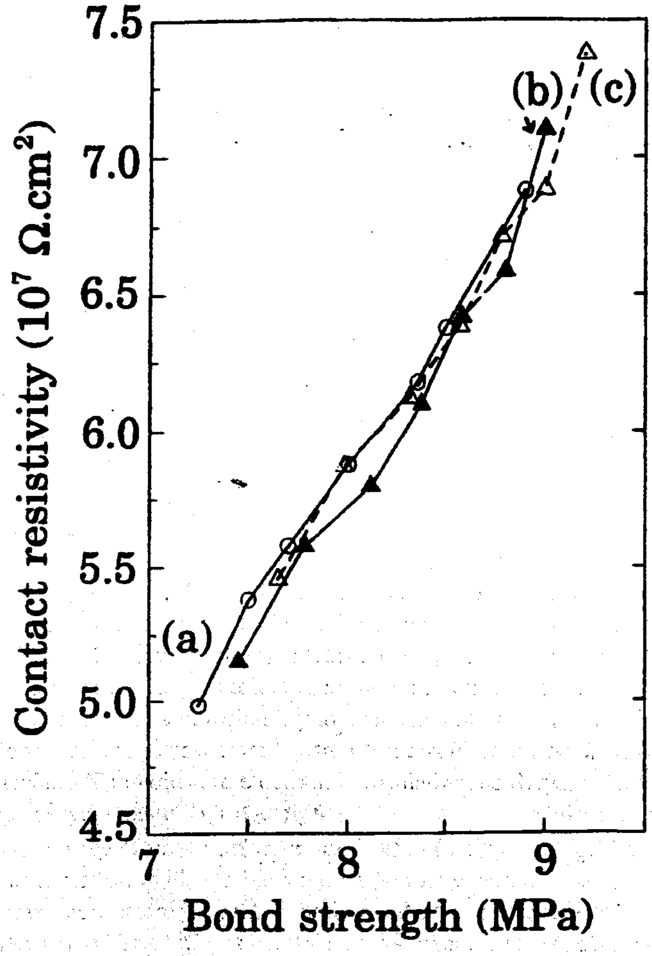

Fig. 4—Variation of contact electrical resistivity with shear bond strength. (a) Concrete with methylcellulose (0.8 percent by weight of cement). (b) Concrete with silica fume and methylcellulose (0.4 percent by weight of cement). (c) Concrete with latex.

Mechanical properties of cement pastes with various admixtures

Table 3 and 4 show a comparison of the tensile and flexural properties of various cement pastes, as previously reported. Latex gives the most attractive tensile and flexural properties, but it is most expensive due to its large amount (20 percent by weight of cement). Methylcellulose gives low tensile modulus, although its small amount (0.4 to 0.8 percent by weight of cement) makes it economical. With both cost and performance considered, methylcellulose (0.4 percent by

Table 3—Effect of admixtures on the tensile properties of cement paste

Admixture	Strength, MPa	Modulus, GPa	Ductility, percent
None*	0.88, ± 4.7 percent	10.9, ± 3.0 percent	0.004, ± 1.0 percent
None†	0.89, ± 3.1 percent	11.13, ± 2.9 percent	0.0052, ± 0.9 percent
Methylcellulose, 0.4 percent by weight of cement*	1.37, ± 2.3 percent	6.6, ± 2.1 percent	0.0209 ± 0.9 percent
Methylcellulose, 0.4 percent by weight of cement†	1.38, ± 3.2 percent	6.89, ± 1.9 percent	0.0213, ± 0.8 percent
Methylcellulose, 0.6 percent by weight of cement†	1.42 ± 2.3 percent	5.95, ± 2.5 percent	0.0254 ± 1.1 percent
Methylcellulose, 0.8 percent by weight of cement†	1.53, ± 2.4 percent	4.74 ± 2.3 percent	0.0375, ± 1.2 percent
Methylcellulose, 0.4 percent by weight of cement + silica fume*	0.83 ± 5.2 percent	40 ± 1.2 percent	0.0088, ± 1.1 percent
Latex*	3.03, ± 4.5 percent	11.5 ± 2.1 percent	0.0352, ± 1.2 percent

*7 days of curing (Reference 22).
†28 days of curing (Reference 21).

weight of cement) in combination with silica fume is most attractive; it gives high tensile modulus, tensile ductility, flexural strength and flexural toughness. The combined use of latex and silica fume causes the workability to be so low that the resulting paste exhibits very poor mechanical properties.

DISCUSSION

The adhesion of concrete to mild steel reinforcing bar, of cement paste to stainless steel fiber and of cement paste to carbon fiber was improved by addition of methylcellulose (as little as 0.4 percent by weight of cement) to the concrete or cement paste. In each case, the increase in shear bond strength was accompanied by negligible increase in the contact electrical resistivity. The addition of latex (20 percent by weight of cement) gave similar bond strength increase as the addition of methylcellulose in each case, even though latex was used in much larger quantity than methylcellulose. In each case, latex addition caused the contact resistivity to increase, suggesting the presence of a latex interfacial layer. The absence of a contact resistivity increase upon methylcellulose addition suggests that the methylcellulose interfacial layer, if any, is thin. The difference in contact resistivity between methylcellulose and latex cases is consistent with the difference in volume resistivity of concrete with methylcellulose and concrete with latex. In spite of this, methylcellulose addition is as effective as latex addition in enhancing adhesion. The effectiveness of methylcellulose compared to latex in adhesion promotion is probably related to the fact that methylcellulose was dissolved in water whereas latex was in the form of a particle dispersion. The liquid solution was probably more

Table 4—Effect of admixtures on the flexural properties of cement paste

Admixture	Strength, MPa	Toughness MPa.mm
None*	2.24, ± 3.2 percent	0.056
Methylcellulose, 0.4 percent by weight of cement*	2.29, ± 3.2 percent	0.105
Methylcellulose, 0.4 percent by weight of cement + silica fume*	2.79, ± 2.2 percent	0.193
Latex*	3.62, ± 4.2 percent	0.202

*7 days of curing (Reference 24).

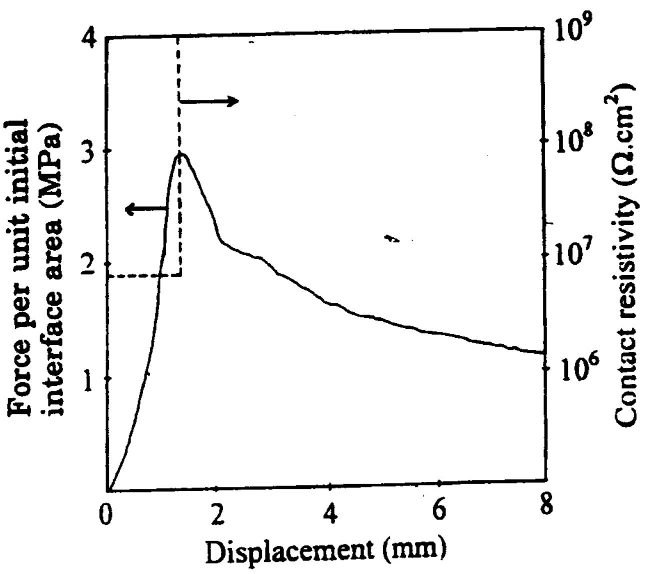

Fig. 5—Plots of force per unit initial interface area versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pull-out testing of steel fiber from cement paste with methylcellulose.

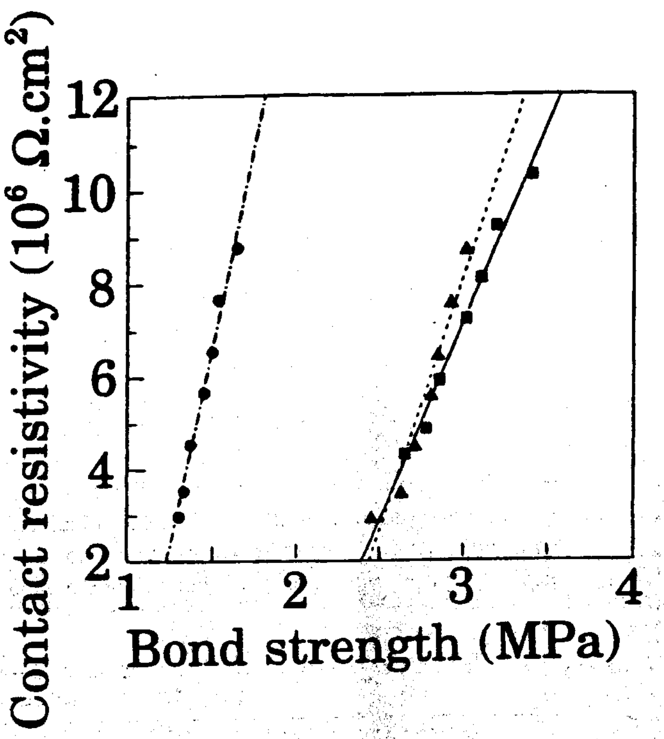

Fig. 6—Correlation of the contact electrical resistivity with the bond strength for the interface between stainless steel fiber and cement paste at 28 days of curing. ●: plain cement paste; ▲: cement paste with methylcellulose; ■: cement paste with latex.

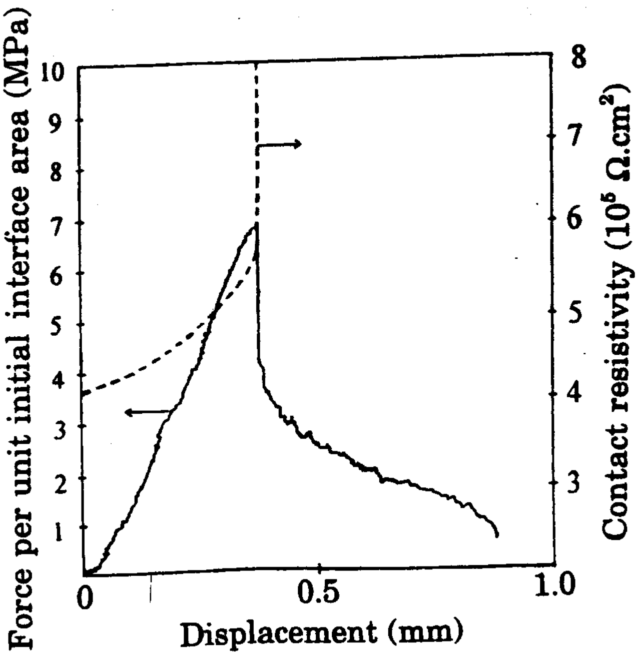

Fig. 7—Plots of force per unit initial interface area versus displacement (solid curve) and of contact electrical resistivity versus displacement (dashed curve) simultaneously obtained during pull-out testing of carbon fiber from plain cement paste.

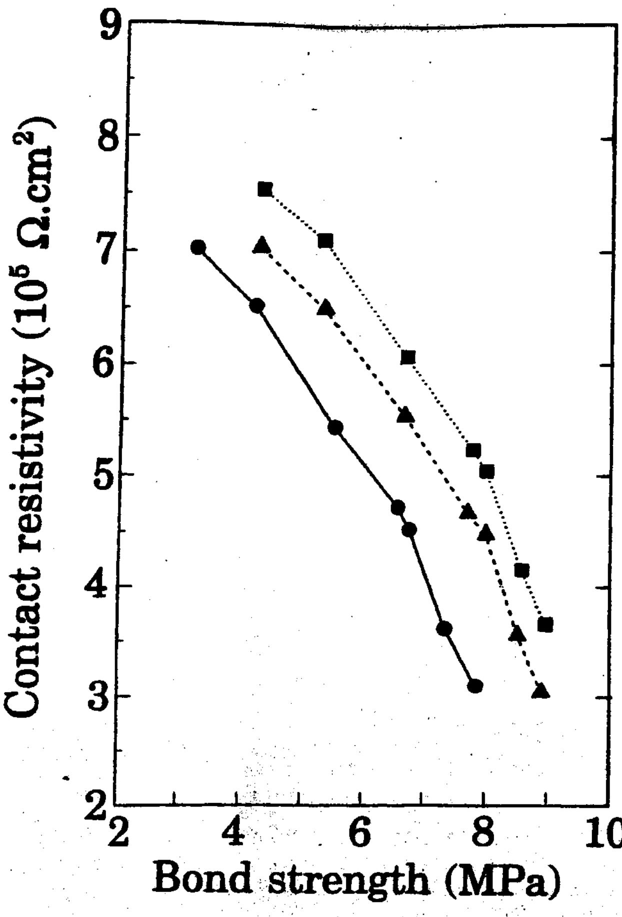

Fig. 8—Variation of contact electrical resistivity with bond strength for carbon fibers in contact with ●: plain cement, ▲: cement with methylcellulose, and ■: cement with latex.

fluid than the dispersion, so it could spread out more easily than the dispersion.

CONCLUSION

The addition of methylcellulose (0.4 to 0.8 percent by weight of cement) to cement paste or concrete was effective for enhancing the adhesion with reinforcements, namely mild steel reinforcing bar, stainless steel fiber and carbon fiber. The bond strength increased with increasing methylcellulose amount, reaching values similar to that obtained by using latex (20 percent by weight of cement). Methylcellulose addition led to essentially no change in the contact electrical resistivity, whereas latex addition led to increase in this resistivity.

The combined use of silica fume (15 percent by weight of cement) and methylcellulose (0.4 percent by weight of cement) as admixtures was found to give concrete that exhibited high bond strength to steel reinforcing bar, in addition to previously reported high tensile modulus, tensile ductility, flexural strength and flexural toughness. The bond strength attained was essentially the same as that attained by using either latex (20 percent by weight of cement) or methylcellulose (0.8 percent by weight of cement) as admixture. The bond strength attained was higher than that attained by using either silica fume or methylcellulose (0.4 percent by weight of cement) alone. Latex in combination with silica fume did not work due to low workability. Methylcellulose in combination with silica fume was effective due to silica fume increasing the matrix modulus and methylcellulose promoting adhesion.

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