Pergamon

Cement and Concrete Research, Vol. 28, No. 4, pp. 487–492, 1998

0008-8846/98 $19.00 + .00

PII S0008-8846(98)00016-7

COMBINED USE OF SILICA FUME AND METHYLCELLULOSE AS ADMIXTURES IN CONCRETE FOR INCREASING THE BOND STRENGTH BETWEEN CONCRETE AND STEEL REBAR

X. Fu and D.D.L. Chung[1]
Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400

(Received September 23, 1997; in final form January 16, 1998)

ABSTRACT

The combined use of silica fume (15% by weight of cement) and methylcellulose (0.4% by weight of cement) as admixtures was found to give concrete that exhibited high bond strength to steel rebar, 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 latex (20% by weight of cement) as admixture. 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's increasing of the matrix modulus and methylcellulose's promotion of adhesion. © *1998 Elsevier Science Ltd*

Introduction

The bond strength between concrete and steel rebar is critical to the performance of steel-reinforced concrete. This strength depends on the ingredients in the concrete mix. It has been reported that silica fume added to the mix increases this strength, because of densification of the steel-paste transition zone (1,2). It has also been reported that a polymer (latex or methylcellulose) added to the mix increases this strength, because of the adhesion provided by the polymer at the steel-concrete interface (3). This paper reports that the use of silica fume and methylcellulose in combination enables the bond strength to be higher than what can be attained by using these additives separately. Moreover, this paper provides a comparative study of the effects of silica fume (15% by weight of cement), methylcellulose (0.4, 0.6 and 0.8% by weight of cement), latex (20% by weight of cement), and silica fume (15% by weight of cement) in combination with methylcellulose (0.4% by weight of cement).

Communicated by D.M. Roy.
[1]To whom correspondence should be addressed.

Experimental Methods

The concrete was made with Portland cement (Type I, from Lafarge Corp., Southfield, MI), fine aggregate (natural sand, all of which passed through a #4 U.S. sieve) and coarse aggregate (all of which passed through a 1-inch 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% by weight of cement. Five types of concrete were used, 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 (Dow Chemical, Midland, MI, Methocel A15-LV) in amounts of 0.4, 0.6, and 0.8% by weight of cement was used in Concrete 2. Methylcellulose in the amount of 0.4% by weight of cement was used in Concrete 5. The defoamer (Colloids, Inc., Marietta, GA, 1010) used along with methylcellulose 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 3 was a styrene-butadiene copolymer; it was used in the amount of 20% by weight of cement. The antifoam (Dow Corning, Midland, MI 2210) used was in the amount of 0.5% by weight of the latex; it was used whenever latex was used. Silica fume (Elkem Materials Inc., Pittsburgh, PA, EMS965) used in Concretes 4 and 5 was in the amount of 15% by weight of cement.

All ingredients were mixed in a stone concrete mixer for 15–20 min. Then the concrete mix was poured into a $6 \times 6 \times 6$ in ($15.2 \times 15.2 \times 15.2$ 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 40%. 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 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 ($14 \times 4 \times 4$ 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% 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% 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 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. 4). Each of one current contact and one voltage contact was situated 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 inches (5 cm) from the top surface of the concrete, while the current contact was in a plane about 4 inches (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

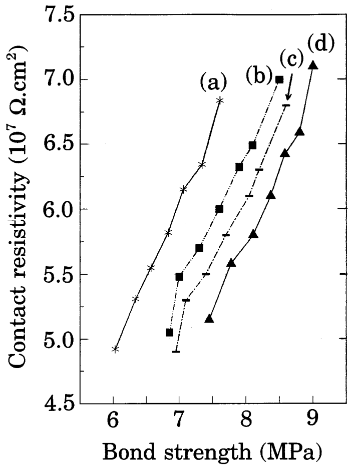

FIG. 1.

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

(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 give above) was subtracted from the measured resistance in order to obtain the contact resistance. The contact resistivity (in $\Omega \cdot cm^2$) 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 Figure 2 of Ref. 4 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. At least seven samples were tested for each concrete.

Results and Discussion

Figures 1 and 2 show the correlation of the contact resistivity with the shear bond strength. The contact resistivity increased roughly linearly with increasing bond strength (as in Ref. 4), such that the data for the different concretes lie on essentially parallel straight lines. Figure 1 shows that methylcellulose (0.4% by weight of cement) increased the bond strength more than silica fume, while methylcellulose (0.4% by weight of cement) in combination with silica fume gave higher bond strength than either silica fume or methylcellulose alone. Silica

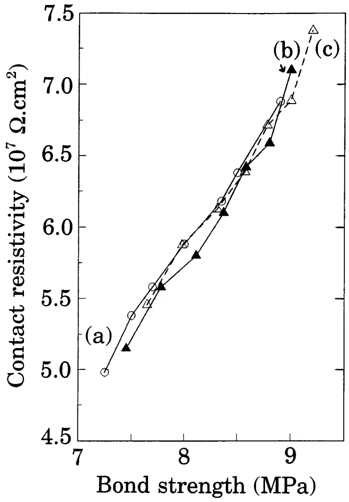

FIG. 2.
Variation of contact electrical resistivity with shear bond strength. (*a*) Concrete with methylcellulose (0.8% by weight of cement). (*b*) Concrete with silica fume and methylcellulose (0.4% by weight of cement). (*c*) Concrete with latex.

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 void content. Figure 2 shows that methylcellulose (0.8% by weight of cement) gave essentially the same bond strength as methylcellulose (0.4% by weight of cement) in combination with silica fume, and also essentially the same bond strength as latex (20% by weight of cement). The bond strength increased monotonically with increasing methylcellulose amount (from 0.4 to 0.6 and to 0.8% by weight of cement), although the data for methylcellulose in the amount of 0.6% by weight of cement are not shown in Figures 1 or 2.

Tables 1 and 2 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% by weight of cement). Methylcellulose gives low tensile modulus, although its small amount (0.4–0.8% by weight of cement) makes it economical. With both cost and performance considered, methylcellulose (0.4% by 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. Methylcellulose differs from latex in that methylcellulose is in the form of a liquid solution, whereas latex is in the form of a solid particle dispersion, when each is added to the concrete mix. The liquid form probably allows methylcellulose to be uniformly distributed even when its concentration is low, so that it is effective even at a low concentration. The low concentration in turn helps to maintain workability to the mix. On the other hand, the dispersion form of latex results in the need for a high latex concentration in the mix in order for the latex to be effective.

The effectiveness of silica fume in combination with methylcellulose as admixtures is due

TABLE 1
Effect of admixtures on the tensile properties of cement paste.

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

*7 days of curing (From Ref. 6)
†28 days of curing (From Ref. 5)

to the combined effect in which silica fume causes matrix modulus increase (rather than interfacial void content decrease) while methylcellulose improves adhesion.

Conclusion

The combined use of silica fume (15% by weight of cement) and methylcellulose (0.4% by weight of cement) as admixtures was found to give concrete that exhibited high bond strength to steel rebar, 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% by weight of cement) or methylcellulose (0.8% by weight of cement) as admixture. The bond strength attained was higher than that attained by using either silica fume or methylcellulose (0.4% by weight of cement) 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.

TABLE 2
Effect of admixtures on the flexural properties of cement paste.

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

*7 days of curing (From Ref. 7).

References

1. T.A. Bürge, Bond in Concrete. P. Bartos (ed.), pp. 273–281, Applied Science Publishers, London, 1982.
2. O.E. Gjorv, P.J.M. Monteiro, and P.K. Mehta, ACI Mater. J. 87, 573 (1990).
3. X. Fu and D.D.L. Chung, Cem. Concr. Res. 27, 643 (1997).
4. X. Fu and D.D.L. Chung, Cem. Concr. Res. 25, 1397 (1995).
5. X. Fu and D.D.L. Chung, Cem. Concr. Res. 26, 535 (1996).
6. P. Chen, X. Fu, and D.D.L. Chung, ACI Mater. J. 94, 147 (1997).
7. P. Chen, Ph.D. Carbon Fiber-Reinforced Concrete as a Strain/Stress Sensor and High-Performance Civil Structure Material. Buffalo, NY: State University of New York at Buffalo; Ph.D. Dissertation, 1994.