Pergamon

Cement and Concrete Research, Vol. 27, No. 12, pp. 1805–1809, 1997

0008-8846/97 $17.00 + .00

PII S0008-8846(97)00173-7

IMPROVING THE BOND STRENGTH BETWEEN STEEL REBAR AND CONCRETE BY INCREASING THE WATER/CEMENT RATIO

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(Communicated by D.M. Roy)
(Received June 19, 1997; in final form September 4, 1997)

ABSTRACT

The bond strength between steel rebar and concrete was found to increase monotonically with an increasing water/cement ratio from 0.45 to 0.60, while the contact electrical resistivity between rebar and concrete decreased slightly. Both effects are due to the decrease of the interfacial void content, which results from the increase in the fluidity of the concrete mix. An increase in bond strength was also observed when a water-wetted rebar was in place of a dry rebar, although the increase was less than that obtained by increasing the water/cement ratio. © *1997 Elsevier Science Ltd*

Introduction

An increase in the water/cement ratio (w/c) is known to decrease the compressive and tensile strengths and increase the drying shrinkage of concrete. As a result, this ratio, in practice, is kept low, although it must not be so low that the workability of the concrete is unacceptably low. Much attention has been given to the effect of the w/c ratio on the properties of concrete and on the bond between steel rebar and concrete. It has been reported that the bond strength increases with increasing tensile strength (1) and compressive strength (2) of the concrete; as the strengths decrease with increasing w/c ratio, the bond strength has been taken to decrease with increasing w/c ratio (1). The pull-out test is commonly used to measure the steel-concrete shear bond strength (3,4), but its result is limited in accuracy due to the data scatter. This problem has been alleviated by the measurement of both bond strength and contact electrical resistivity on each sample and by correlating these two quantities (5–11). By using this technique (called electromechanical testing) in this work, we found that the bond strength actually *increases* with increasing w/c ratio from 0.45 to 0.60.

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 a #4 U.S. sieve), and coarse

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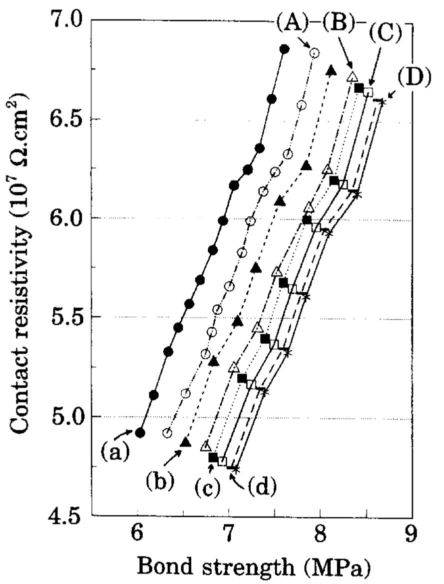

FIG. 1.

Variation of contact electrical resistivity with shear bond strength between steel rebar and concrete of water/cement ratio (*a*) 0.45, (*b*) 0.50, (*c*) 0.55 and (*d*) 0.60, all cured at 40% relative humidity, and between steel rebar and concrete of water/cement ratio (*A*) 0.45, (*B*) 0.50, (*C*) 0.55, and (*D*) 0.60, all cured at 100% relative humidity.

aggregate (all of which passed through a 1-inch sieve) in the weight ratio 1:1.5:2.49. The w/c ratio was 0.45, 0.50, 0.55, or 0.60. 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 to 20 min. Then the concrete mix was poured into a 6 × 6 × 6 inch (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 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 relative humidities of 40% and 100%. 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 1.50×10^7, 1.48×10^7, 1.46×10^7, and 1.45×10^7 Ω·cm for water/cement ratios of 0.45, 0.50, 0.55, and 0.60 respectively, as obtained by the four-probe method, in which all four probes (silver paint) were around the whole perimeter of the concrete specimen (16 × 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 Figure 1 of Ref. 5. Each current contact and voltage contact was circumferentially on the rebar. The other voltage and current contacts were on the concrete embedding

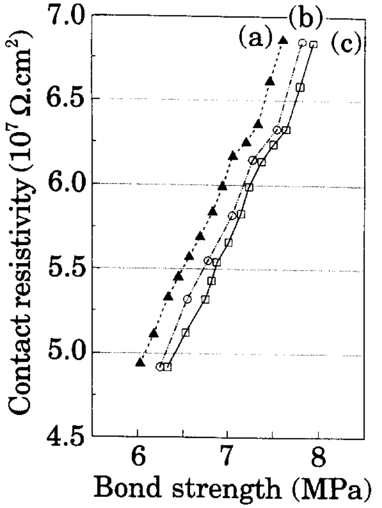

FIG. 2.

Variation of contact electrical resistivity with shear bond strength between steel rebar and concrete of water/cement ratio 0.45. (*a*) Dry rebar, 40% humidity (*b*) Wet rebar, 40% humidity, (*c*) Dry rebar, 100% humidity. (*a*) is the same as Fig. 1 (*a*). (*c*) is the same as Fig. 1 (*A*).

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 inch (5 cm) from the top surface of the concrete, while the current contact was in a plane about 4 inch (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 could be neglected and that of the concrete could not. 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 $\Omega \cdot cm^2$) 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. 5 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 combination of w/c ratio and relative humidity.

Results and Discussion

Figure 1 shows the correlation of the contact resistivity with the bond strength for concretes cured at relative humidities of 40% and 100%. The contact resistivity increased roughly linearly with increasing bond strength (as in Ref. 5), such that the data for the different w/c ratios lie on essentially parallel straight lines. For each humidity value, the greater was the w/c ratio, the higher was the bond strength, and the slightly lower was the contact resistivity. The increase in bond strength was greatest (fractional increase $\simeq$7%) when the water/cement ratio was increased from 0.45 to 0.50, less when the ratio was increased from 0.50 to 0.55, and still less when the ratio was increased from 0.55 to 0.60. For the same w/c ratio, the bond strength increased when the humidity was increased from 40% to 100%; this effect became smaller as the w/c ratio increased.

The increase in bond strength and the decrease in contact resistivity upon increase in the w/c ratio are both attributed to the decrease in the interfacial void content. An increase in the water/cement ratio increased the fluidity of the concrete mix, thereby allowing the mix to fill the gap between rebar and concrete more completely. The slump was 138, 156, 180, and 200 mm at a w/c ratio of 0.45, 0.50, 0.55, and 0.60, respectively. Although a vibrator was used to help consolidation, the degree of consolidation was not perfect. That the bond strength increased with humidity is consistent with this trend.

Due to the decrease of the compressive strength with increasing w/c ratio, increasing the w/c ratio for the entire concrete is not practical for most structures. However, the local water/cement ratio around a steel rebar was effectively increased in a separate experiment in this work by using a rebar that had been wetted with water (1% weight increase after wetting) just prior to embedding the rebar in concrete of water/cement ratio 0.45 and curing the concrete at a relative humidity of 40%. The use of the wet rebar indeed resulted in increased bond strength, although the effect was not as much as that of increasing the w/c ratio from 0.45 to 0.50 or that of increasing the relative humidity from 40% to 100%. Figure 2 shows the comparison between dry rebar and wet rebar cases, both for w/c ratio 0.45 and relative humidity 40%.

Our earlier work had shown that latex addition to concrete and/or oxidation (with water or ozone) treatment of steel rebar increased both the bond strength and the contact resistivity (5,6), due to the formation of an interfacial layer of high volume resistivity. This interlayer was latex, in the case of latex addition to concrete and an iron oxide, in the case of oxidation treatment of rebar. In contrast, in this work, we found that an increase of the w/c ratio increased the bond strength but decreased the contact resistivity, due to the interfacial voids.

The compressive strength of concrete is known to decrease with increasing w/c ratio, but the bond strength between steel rebar and concrete increases with increasing w/c ratio. The magnitude of the fractional change in concrete strength is about twice that of the fractional change in bond strength for the same increase in w/c ratio. These opposite trends should be taken into account in determining the optimum w/c ratio for steel reinforced concrete, especially for prefabricated structural components that require a high bond strength. In current practice, the w/c ratio is chosen mainly based on consideration of the compressive strength of the concrete. In addition to increasing the bond strength, a high w/c ratio reduces the material cost.

Conclusion

At a fixed humidity (whether 40% or 100%), the bond strength between steel rebar and concrete was found to increase monotonically with increasing w/c ratio from 0.45 to 0.60.

Accompanying the bond strength increase was a slight decrease of the contact resistivity. Both effects are attributed to decrease of the interfacial void content, which results from the increase in fluidity of the concrete mix. The effect of w/c ratio on the bond strength became less as the w/c ratio increased. Increase of the humidity from 40% to 100% increased the bond strength; the effect became less as the w/c ratio increased. The use of a rebar that was wet with water, instead of a dry rebar, also caused the bond strength to increase, but the effect was smaller than that resulting from humidity increase or w/c ratio increase.

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