Pergamon

Cement and Concrete Research, Vol. 27, No. 5, pp. 649-656, 1997

0008-8846/97 $17.00 + .00

PII S0008-8846(97)00058-6

CATHODIC PROTECTION OF STEEL REINFORCED CONCRETE FACILITATED BY USING CARBON FIBER REINFORCED MORTAR OR CONCRETE

Jiangyuan Hou and D.D.L. Chung

Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400

(Communicated by D.M. Roy)
(Received February 4, 1997; in final form March 21, 1997)

ABSTRACT

Due to the decrease in volume electrical resistivity associated with carbon fiber addition (0.35 vol.%) to concrete (embedding steel rebar), concrete containing carbon fibers and silica fume reduced by 18% the driving voltage required for cathodic protection compared to plain concrete, and by 28% compared to concrete with silica fume. Due to the decrease in resistivity associated with carbon fiber addition (1.1 vol.%) to mortar, overlay (embedding titanium wires for electrical contacts to steel reinforced concrete) in the form of mortar containing carbon fibers and latex reduced by the 10% the driving voltage required for cathodic protection, compared to plain mortar overlay. In spite of the low resistivity of mortar overlay with carbon fibers, cathodic protection required multiple metal electrical contacts embedded in the mortar at a spacing of 11 cm or less. © *1997 Elsevier Science Ltd*

Introduction

Cathodic protection is one of the most common and effective methods for corrosion control of steel reinforced concrete (1-4). This method involves the application of a voltage so as to force electrons to go to the steel rebar, thereby making the steel a cathode. As the steel rebar is embedded in concrete, the electrons need to go through the concrete in order to reach the rebar. However, concrete is not very conducting electrically. An objective of this work is to investigate the use of carbon fiber reinforced concrete for embedding the rebar to be cathodically protected, as the short carbon fibers enhance the conductivity of the concrete.

For directing electrons to the steel reinforced concrete to be cathodically protected, an electrical contact is needed on the concrete. The electrical contact is electrically connected to the voltage supply. One of the choices of an electrical contact material is zinc, which is a coating deposited on the concrete by thermal spraying. It has a very low volume resistivity (thus requiring no metal mesh embedment), but it suffers from poor wear and corrosion resistance, the tendency to oxidize, high thermal expansion coefficient, and high material and processing costs. Another choice is a conductor filled polymer (5), which can be applied as a coating without heating, but it suffers from poor wear resistance, high thermal expansion coefficient and high material cost. Yet another choice is a metal (e.g., titanium) strip or wire embedded at one end in cement mortar, which is in the form of a coating on the steel reinforced concrete. The other objective of this work is to investigate the use of carbon fiber reinforced mortar for this coating, as it is advantageous to enhance the conductivity of this coating.

Carbon fiber reinforced concrete or mortar had been studied in terms of its electrical, mechanical and other properties (6-11). The use of carbon fiber reinforced mortar as an electrical contact coating on old (cured) mortar was suggested, based on the low volume resistivity of the carbon fiber reinforced mortar and the low contact resistivity between carbon fiber reinforced mortar and old mortar (12). The low contact resistivity is related to the low drying shrinkage of carbon fiber reinforced mortar and the resulting high bond strength between carbon fiber reinforced mortar and the underlying old mortar, which has finished its drying shrinkage (13). The use of carbon fiber reinforced mortar as an electrical contact to a metal was also shown (14). Nevertheless, the use of carbon fiber reinforced mortar or concrete for cathodic protection was not demonstrated.

Experimental Methods

Cathodic protection of mild steel rebar (size #3, length 2.3 cm, diameter 0.92 cm, with surface deformation in the form of off-axis ridges of pitch 6 mm, sand blasted for cleaning prior to embedding in concrete) in concretes was tested using two experimental configurations (Fig. 1 and 2). In both configurations, a titanium wire of diameter 1 mm was used as the electrical contact, which was wound around the concrete cylinder (7.8 cm diameter and 15 cm height) and then embedded in a mortar overlay, such that the free end of the wire protruded from the overlay and was connected to the positive pole of a DC power supply (Harrison 6294A). The rebar was at the center of the concrete cylinder along the axis of the cylinder, such that its

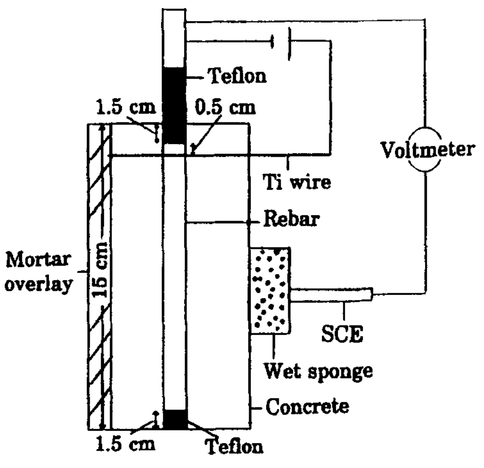

FIG. 1.
Schematic picture of cathodic protection system using one Ti wire.

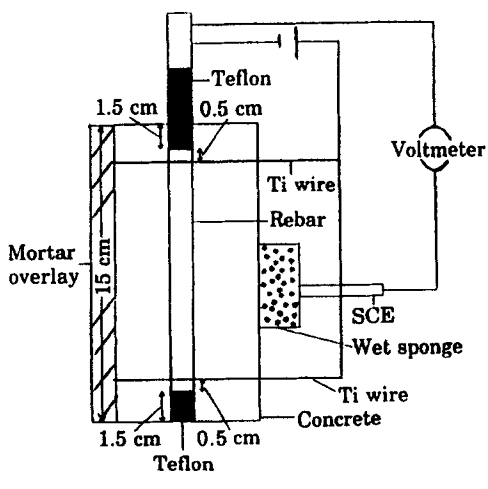

FIG. 2.
Schematic picture of cathodic protection system using two Ti wires.

bottom was at the bottom of the cylinder and its top was above the top of the cylinder. The exposed top end of the rebar was connected to the negative pole of the power supply. In order to define clearly the length of the rebar that was in contact with the concrete, the bottom 1.5 cm of rebar and the top 1.5 cm of rebar within the cylinder were covered with teflon tape. Mortar of thickness 5 cm was applied on the cylindrical surface of the concrete cylinder, such that it covered the whole length of the concrete cylinder, but only 30% of the area of the cylindrical surface of the concrete. A saturated calomel electrode (SCE) serving as the reference electrode was used to measure the potential of the rebar. The electrode had tip diameter 2 mm and glass casing diameter 1.5 cm. It was put on the cylindrical surface of the concrete through a piece of wet sponge of thickness 2 cm before squeezing and 2 mm during squeezing, which occured during the experiment. The area of the sponge in close contact with the concrete surface was 2 cm in diameter. The electrode was moved on the concrete surface in the axial direction in steps of 1 cm in order to study the variation of the rebar potential with the distance along the rebar. Cathodic protection is said to be complete when the potential is -0.77 V versus SCE (15). The difference between Fig. 1 and 2 is that Fig. 1 has one Ti wire whereas Fig. 2 has two Ti wires. Each Ti wire was at a distance of 0.5 cm from the end of the rebar which was not covered by teflon.

The carbon fibers were short (nominally 5 mm in length), 10 μm in diameter, 3×10^{-3} Ω.cm in volume electrical resistivity, 48 GPa in tensile modulus, 690 MPa in tensile strength, unsized and made from isotropic pitch. They were provided by Ashland Petroleum Co. (Ashland, Kentucky). The dispersion of the carbon fibers requires additives, such as latex, methylcellulose and/or silica fume. Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used. The sand was natural sand (all passing #4 US sieve, 99.9% SiO_2), with particle size analysis shown in Fig. 1 of Ref. 16. The sand/cement ratio was 1.5. The water/cement ratio was 0.5, unless noted otherwise.

Three types of concrete were used to embed the steel rebar. They were (i) plain concrete, (ii) concrete with silica fume and (iii) concrete with carbon fibers, methylcellulose and silica fume. Carbon fibers in the amount of 0.35 vol.% (corresponding to 0.5% by weight of cement) were used. The water reducing agent powder was TAMOL SN (Rohm and Haas), which contained 93-96% sodium salt of a condensed naphthalene sulfonic acid; it was used in the amount of 2% by weight of cement, except that it was not used in plain concrete. The silica fume (Elkem Materials, EMS 960) was used in the amount of 15% by weight of cement. Methylcellulose (Dow Chemical, Methocel A15-LV) in the amount of 0.4% of the cement weight was used. A defoamer (Colloids 1010) was added in the amount of 0.13 vol.% whenever methylcellulose was used. The coarse aggregate (all passing 1 in. sieve) was such that the cement, sand and coarse aggregate were in the weight ratio 1 : 1.5 : 2.49.

Two types of mortar were used for the overlay on the concrete. They were (i) plain mortar and (ii) mortar with latex and carbon fibers. The water/cement ratio was 0.5 for the former and 0.4 for the latter. Carbon fibers in the amount of 1.1 vol.% (corresponding to 1.5% by weight of cement) were used. The latex (Dow Chemical, 460 NA) was a styrene butadiene copolymer; it was used in the amount of 20% of the weight of the cement. An antifoam agent (Dow Corning 2410) in the amount of 0.5% of the weight of the latex was used whenever latex was used.

All ingredients except the coarse aggregate were mixed to form a mortar, using a Hobart mixer with a flat beater. For concretes, the coarse aggregate was subsequently added and mixed with a 2CM concrete mixer (Stone Construction Equipment, Inc., Honeoye, New York) before being poured into plastic cylindrical molds of diameter 7.8 cm and height 15 cm. Oil was applied to the inner surface of the molds before the concrete mix was poured into the mold, while a rebar was positioned vertically and held in place at the center of the bottom inside surface of the mold. After pouring, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The cylinders were demolded after 24 h and then cured in air with a relative humidity of 33%. After curing for 28 days, Ti wire was fastened to the cylinder (Fig. 1 and 2) and then the mortar overlay was applied on the cylindrical surface of the concrete. The whole system was cured 7 more days before testing.

Steel reinforced concrete samples were immersed in a saturated $Ca(OH)_2$ solution for 24 h for a stable corrosion potential of rebar to develop and then removed from the solution. Excessive solution on the surface was wiped out. An SCE reference electrode was used to measure the potential.

The volume electrical resistivity was measured on concrete samples (without rebars) that were cylinders of 7.8 cm diameter and 15 cm height. They had been cured in air at a relative humidity of 33% for 28 days. The resistivity was measured by the four-probe method, in which all four probes (silver paint) were placed around the whole perimeter of the concrete specimen in four parallel planes perpendicular to the cylindrical axis of the specimen. The outer probes (11 cm apart) were for passing a DC current; the inner probes (7 cm apart) were for voltage measurement.

Results and Discussion

Effect of Cathodic Protection Configuration. The cathodic protection system was first set up as shown in Fig. 1, where only one Ti wire was applied at one end of the reinforced concrete sample as the electrical contact. The concrete sample was plain concrete; the overlay was mortar containing 1.1 vol.% carbon fibers and latex. The initial potential of rebar before cathodic protection was -380 mV anywhere along the length of rebar. After turning on the power, the potential was -770 mV up to a distance of 2 cm from the Ti wire and it became less negative as the distance increased. Fig. 3 is a plot of the rebar potential versus distance (projected distance from Ti wire on cylindrical axis of the sample) at an applied voltage of 2.05 V. Thus, one Ti wire was ineffective for the overall cathodic protection of the 15 cm long sample. In spite for the higher conductivity of carbon fiber mortar overlay compared to plain mortar overlay, the use of more than one Ti wire was necessary, whether carbon fibers were present in the overlay or not.

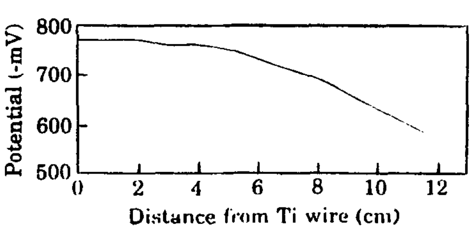

FIG. 3.
Potential of rebar in cathodic protection system using carbon fiber mortar as the overlay (with one Ti wire).

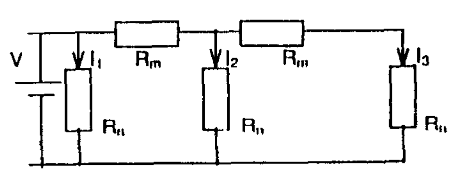

FIG. 4.
Circuit model for configuration of Fig. 1.

For cathodic protection, current must travel along the overlay parallel to the axis of the concrete cylinder as well as travelling radially toward the rebar. The resistances include axial volume resistance of the overlay (R_v), radial contact resistance (R_c) of the overlay-concrete interface, radial volume resistance of the concrete and radial contact resistance of concrete-steel interface. The volume resistance of the steel is negligibly small. The axial volume resistance of the concrete is much higher than that of the mortar overlay. R_c and R_v are given by

$$R_v = \rho_v \frac{L}{t \times w}, \quad \text{and} \quad R_c = \frac{\rho_c}{L \times w},$$

where ρ_v is the volume resistivity of the mortar overlay, ρ_c is the contact resistivity of the mortar-concrete interface, L is the length of overlay along the direction parallel to the rebar, t is the thickness of the overlay and w is the width of the overlay. According to Ref. 12, $\rho_v = 1.16 \times 10^2$ Ω.cm² and $\rho_c = 2.65 \times 10^4$ Ω.cm². In this work, L, t and w are 12.5, 5 and 6.1 cm respectively. It can be seen from the above equations that R_v is 47.4 Ω and R_c is 346 Ω. The measured volume resistivity of the plain concrete was $(9.5 \pm 0.5) \times 10^8$ Ω.cm, so the radial resistance of the concrete = 2.8×10^8 Ω. The contact resistivity of the concrete-steel interface was $(5.8 \pm 1.0) \times 10^7$ Ω.cm² [17], so the contact resistance of this interface = 2.1×10^8 Ω. Thus, the three radial resistances are dominated by the volume resistance of the concrete and the contact resistance of the concrete-steel interface.

With only one Ti wire, the circuit model of the cathodic protection system is as shown in Fig. 4, where R_m is the axial resistance of a part (half of the length of rebar in the circuit model) of the mortar overlay and R_n is the radial resistance of a part (one-third in this model) of the concrete matrix, together with the overlay-concrete contact resistance and concrete-steel contact resistance for the corresponding part. Current (I_1, I_2, I_3) radially from the overlay to the rebar is large enough for the part of the length of the rebar which is cathodically protected, such that the current diminishes as the distance between the point along the length of rebar and the Ti wire increases (i.e., $I_1 > I_2 > I_3$ and $I_1 = V/R_n$). By dividing the length of rebar into 499 parts rather than 2 parts (Fig. 4), the current to each part was calculated, as shown in Fig. 5 in terms of current density at rebar surface vs. distance along rebar from the Ti wire. Figures 3 and 5 are consistent in showing that the extent of cathodic protection drops significantly when the distance from the Ti wire exceeds 8 cm.

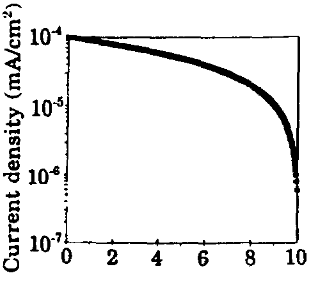

FIG. 5.
Current density radially to rebar surface vs. distance along rebar from the Ti wire for configuration of Fig. 1.

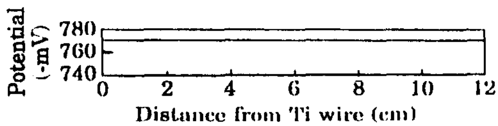

FIG. 6.
Potential of rebar in cathodic protection system using carbon fiber mortar as the overlay (with two Ti wires).

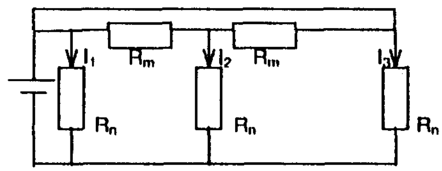

FIG. 7.
Circuit model for configuration of Fig. 2.

Due to the undesirable result obtained with the configuration of Fig. 1, another Ti wire was fastened to the other end of the reinforced concrete cylinder (Fig. 2). The two Ti wires were 11 cm apart. The concrete was plain concrete, while two kinds of mortar were used for the overlay -plain mortar and mortar containing latex and 1.1 vol.% carbon fibers. With either kind of overlay, the potential distribution was uniform (Fig. 6).

The circuit model (Fig. 7) for two Ti wires being used is different from the one with one Ti wire in that the axial resistance R_m of the overlay is almost shunted by the two Ti wires, which are both connected to the positive pole of the voltage supply. Thus, R_m has much less influence when two Ti wires are used than when one Ti wire is used. Current is spread by two Ti wires, but it still has to go through R_m to reach the middle part of the rebar length between the two wires. The use of two Ti wires caused the rebar to be protected for a much longer distance than the use of one wire, since, in the two-wire model (Fig. 7), $I_1 = I_3 = V/R_m$ and $I_2 < I_1$. The maximum spacing of Ti wires to provide uniform protection was not determined, though it is more than 11 cm.

Effect of Mortar Overlay. The rebar potential before and after (1-4 days) turning on the power supply for system with plain mortar overlay and that with mortar overlay containing carbon fibers and latex are listed in Table 1. The same voltage (2.8 V) was used for both systems. Before applying the voltage, the potential of the sample with plain mortar overlay was less negative than that of the sample with carbon fiber mortar overlay. However, the potential of the latter dropped to a much more negative level than the former after turning on the power supply. In fact, with a voltage of 2.80 V, the potential of rebar with carbon fiber mortar overlay was -770 mV versus SCE, while the potential of the rebar with plain mortar overlay reached

TABLE 1

Potential (mV, ± 10 vs. SCE) in Plain Concrete With Two Different Mortar Overlays Before and After (1-4 Days) Applying a Voltage of 2.80 V

	Plain	+ latex + 1.1 vol.% fibers
Before	-370	-380
After (1 day)	-710	-770
After (2 days)	-590	-770
After (3 days)	-550	-770
After (4 days)	-550	-770

TABLE 2
Potential (mV, ± 10 vs. SCE) of Rebars in Different Concrete Matrices Before and After (1-4 Days) Applying a Voltage of 2.30 V. Note: M = Methylcellulose, f = Carbon Fibers, SF = Silica Fume

	Plain	+SF	+M+f+SF
Before	-380	-330	-350
After (1 day)	-640	-530	-770
After (2 days)	-630	-520	-770
After (3 days)	-630	-510	-770
After (4 days)	-630	-510	-770

only -550 mV versus SCE. The driving voltage required for rebar in plain concrete to reach the protection criterion -770 mV was 3.10 ± 0.01 V for plain mortar and 2.80 ± 0.01 V for carbon fiber mortar. Hence, the driving voltage required for the plain mortar overlay was 11% higher than that required for the carbon fiber mortar overlay, due to the lower volume resistivity and lower mortar-concrete contact resistivity for the latter. Furthermore, the rebar potential of the sample with plain mortar overlay became less negative as the testing time increased beyond 1 day. This is due to the increased resistivity as the water content decreased. Thus, the configuration of Fig. 2 was effective for cathodic protection of the entire sample; the performance was much better when carbon fiber mortar overlay rather than plain mortar overlay was used.

Effect of Concrete Matrix. The efficiency of the cathodic protection system depends not only on the resistances associated with the overlay, but also the volume resistance of the concrete embedding the rebar. Table 2 lists the rebar potential before and after turning on the power supply for different concretes and the same carbon fiber mortar overlay. The concretes were plain concrete, concrete with only silica fume and concrete with methylcellulose, carbon fibers and silica fume. At a fixed voltage of 2.30 V, only the potential of rebar in the third kind of concrete matrix reached the protection criterion of -770 mV versus SCE; potentials of rebars in plain concrete and concrete with silica fume decreased from their values before the power was turned on, but did not reach -770 mV versus SCE. Due to the lower resistivity of plain concrete ($(9.5 \pm 0.5) \times 10^8$ Ω.cm) compared to concrete with silica fume ($(2.18 \pm 0.05) \times 10^9$ Ω.cm), the former was better than the latter. The driving voltage for systems with carbon fiber mortar overlay to reach the protection criterion of -770 mV versus SCE was 2.80 ± 0.01, 3.20 ± 0.01 and 2.30 ± 0.01 V for plain concrete, concrete with silica fume, and concrete with fibers, methylcellulose and silica fume, respectively.

Conclusion

Due to the decrease in resistivity associated with carbon fiber addition to mortar, overlay (embedding titanium wires for electrical contacts) in the form of mortar containing carbon fibers was more effective than that without fibers in reducing the driving voltage required for cathodic protection of steel reinforced concrete. Due to the decrease in resistivity associated with carbon fiber addition to concrete, concrete containing carbon fibers was more effective than that without fibers in reducing the driving voltage required for cathodic protection. Mortar overlay containing carbon fibers and latex required 10% less driving voltage to protect the rebar in concrete than plain mortar overlay. For the same overlay (containing carbon fibers and latex), rebar in concrete with carbon fibers and silica fume needed 18% less driving voltage than rebar in plain concrete and needed 28% less driving voltage than rebar in concrete containing silica fume only in order to be protected cathodically. This is due to the low resistivity of the concrete with carbon fibers and silica fume, and the high resistivity of the concrete with silica fume only. The use of multiple titanium wires (separated by 11 cm or less) was necessary, whether fibers were present in the overlay or not.

References

1. M. Unz, Corrosion 16, 123 (1960).
2. B. Heuze, Materials Protection 4(11), 57 (1965).
3. D.A. Hausmann, Materials Protection 8(10), 66 (1969).
4. G. Baronio, M. Berra, L. Bertolini, T. Pastore, Cem. Concr. Res. 26(5), 683 (1996).
5. R. Pangrazzi, W.H. Hartt and R. Kessler, Corrosion (Houston) 50(3), 186 (1994).
6. P. Chen and D.D.L. Chung, ACI Materials J. 93(2), 129 (1996).
7. P. Chen and D.D.L. Chung, Composites: Part B; 27B, 269 (1996).
8. X. Yang and D.D.L. Chung, Composites 23(6), 453 (1992).
9. N. Banthia, A. Moncef, K. Chokri and J. Sheng, Can. J. Civ. Eng. 21, 999 (1994).
10. P. Chen and D.D.L. Chung, ACI Materials J. 93(4), 341 (1996).
11. X. Fu and D.D.L. Chung, Cem. Concr. Res. 26(1), 15 (1996).
12. X. Fu and D.D.L. Chung, Cem. Concr. Res. 25(4), 689 (1995).
13. P. Chen, X. Fu and D.D.L. Chung, Cem. Concr. Res. 25(3), 491 (1995).
14. P. Chen and D.D.L. Chung, Smart Mater. Struct. 2, 181 (1993).
15. J.B. Vrable and B.E. Wilde, Corrosion/79, Paper 135, March 12-16, 1979, Atlanta, Georgia.
16. P. Chen and D.D.L. Chung, Smart Mater. Struct. 2, 22 (1993).
17. X. Fu and D.D.L. Chung, Cem. Concr. Res. 25(7), 1397 (1995).