ELECTRICALLY CONDUCTIVE CONCRETE--A LABORATORY STUDY

by

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Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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ABSTRACT

In the cathodic protection of existing reinforced concrete bridge decks, there is a need for a simple secondary-anode system to facilitate the distribution of direct current over the structure being protected. It is believed that a durable, electrically conductive concrete can fill this need by serving both as an overlay and a secondary-anode system. In pursuit of such a system, three relatively conductive concrete mixtures were examined. Two of these mixtures contained carbon fibers alone, whereas the third contained carbon fibers and carbon black.

Comparisons with some physical, mechanical, and electrical properties of a control mixture indicated that a conductive mixture containing fibers alone can be readily designed to be sufficiently durable and conductive to satisfy the need.

TABLE OF CONTENTS

To Convert From	To	Multiply By
Length:		
in	cm	2.54
in	m	0.025 4
ft	m	0.304 8
yd	m	0.914 4
mi	km	1 . 609 344
Area:		
in^2	cm^2	6.451 600 E+00
ft^2	m^2	9.290 304 E-02
yd^2	m^2	8.361 274 E-01
mi^2	Hectares	2.589 988 E+02
acre (a)	Hectares	4.046 856 E-01
Volume:		
oz	m^3	2.957 353 E-05
pt	m^3	4.731 765 E-04
qt	m^3	9.463 529 E-04
gal	m^3	3.785 412 E-03
in^3	m^3	1.638 706 E-05
ft^3	m^3	2.831 685 E-02
yd^3	m^3	7.645 549 E-01
Volume per Unit Time:	NOTE: $1m^3$ = 1,000 L	
ft^3/min	m^3/sec	4.719 474 E-04
ft^3/s	m^3/sec	2.831 685 E-02
in^3/min	m^3/sec	2.731 177 E-07
yd^3/min	m^3/sec	1.274 258 E-02
gal/min	m^3/sec	6.309 020 E-05
Mass:		
oz	kg	2.834 952 E-02
dwt	kg	1.555 174 E-03
lb	kg	4.535 924 E-01
ton (2000 lb)	kg	9.071 847 E+02
Mass per Unit Volume:		
lb/yd^2	kg/m^2	4.394 185 E+01
lb/in^3	kg/m^3	2.767 990 E+04
lb/ft^3	kg/m^3	1.601 846 E+01
lb/yd^3	kg/m^3	5.932 764 E-01
Velocity: (Includes Speed)		
ft/s	m/s	3.048 000 E-01
mi/h	m/s	4.470 400 E-01
knot	m/s	5.144 444 E-01
mi/h	km/h	1.609 344 E+00
Force Per Unit Area:		
lbf/in^2 or psi	Pa	6.894 757 E+03
lbf/ft^2	Pa	4.788 026 E+01
Viscosity:		
cS_t	m^2/s	1.000 000 E-06
P	Pa·s	1.000 000 E-01

Temperature: $(°F-32)^5/9$ = °C

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INTRODUCTION

It was recently reported by this investigator that the electrical resistivity of portland cement concrete, which ranges from approximately 1500 to 5250 ohm-cm, can be significantly reduced to a range of approximately 54 to 274 ohm-cm by the addition of carbon fibers alone or carbon fibers in combination with carbon black (1). Such relatively conductive concrete has a potential use in the cathodic protection (CP) of existing concrete bridge decks against further corrosion of the rebars. After the removal and replacement of deteriorated concrete from a deck, this conductive concrete may be used both as an overlay and a secondary anode to ensure even distribution of protective current over the entire superstructure, thereby simplifying the installation procedure and consequently reducing the cost of CP systems for bridge decks.

As a follow-up to that previous study, three different mixtures of conductive concrete were prepared for further study of some of their physical and mechanical properties. In addition, attempts were made to assess their likely effectiveness in current distribution and their durability when placed in an electrical circuit in a chloride-contaminated environment similar to that existing in an actual bridge deck. Such information would be useful in deciding whether this material warrants testing on an actual bridge deck. This report describes the laboratory procedures used in this assessment and discusses the results obtained.

PROCEDURE

In all three mixtures studied, a type II cement, a coarse granite aggregate (size No. 9, ASTM D448), and a siliceous sand were used. A commercially available, high modulus carbon fiber with a length of 0.25 in was added to two of the mixtures (CF-4 and CF-5) in two different concentrations. The carbon fibers used came from the manufacturer with a moisture content of 21% by weight. In the third mixture, CFC-2, carbon black was also added. The composition and the corresponding physical characteristics of these mixtures and a conventional concrete mixture are shown in Table 1. The conventional concrete mixture, which was equivalent to Virginia class A4 concrete (2), was used as a control.

Table 1

Compositions and Physical Characteristics of the Conductive Concrete Mixes

	Mixture			
	CF-4	CF-5	CFC-2	Control
Coarse Aggregate (%)	19.9	31.4	32.2	52.5
Fine Aggregate (%)	26.8	10.5	10.8	25.8
Cement (%)	30.8	38.3	34.4	15.0
Water (%)	19.3	17.9	19.3	6.7
Carbon Fiber (%)	3.2	1.9	2.2	0.0
Carbon Black (%)	0.0	0.0	1.1	0.0
Air-Entraining Agent*	1.0	1.2	1.6	0.4
Water Reducer*	4.3	4.3	5.2	3.0
W/C (lb water/lb cement)	0.60	0.47	0.56	0.45
Density (lb/ft^3)	124.0	129.0	126.0	175.0
Slump (in)	2.4	2.4	3.4	4.0
Air Content (%)	3.5	5.7	3.5	5.5

*oz/100 lb cement

Except for a few modifications, which concerned the mixing of the materials, the making and curing of test specimens were carried out in accordance with ASTM Method C192. These modifications included the sequence the carbon fibers (and carbon black, if used) and the rest of the ingredients were loaded into the mixer. It was found that to minimize clumping of the fibers, it is best to load these right after the aggregate and before the other materials (including the carbon black, if used). The other modification involved an increase in the mixing time to effect uniform dispersion of the fibers throughout the mixtures.

The test specimens, including those prepared with procedures described later, were tested for the following eight characteristics:

1. Compressive strength at 28 days (ASTM Method 39).

2. Splitting tensile strength at 28 days (ASTM Method C496) to obtain an indication of the cohesion of the hardened conductive concrete.

3. The 28-day bond strength, determined by applying a shear force parallel to the bonding surface of a conductive mixture and the control concrete mixture in a cylindrical specimen made from these mixtures. The bond strength can serve as a useful measure of the comparative ability of a conductive concrete, which will be used as an overlay, to adhere to a concrete base.

   The procedure used in the preparation of the specimens for this test and the quillotine-like apparatus used to apply the shearing force were described in the earlier report (1).

4. Thermal stability, determined by measuring the bond strength of some specimens after being subjected to different numbers of cycles of change in air temperature from 0°F to 100°F (at a rate of three cycles per day).

5. The resistance to rapid freezing and thawing, determined by using ASTM Method C666 (Procedure A) with two modifications: one in the curing of the specimens and the other in the addition of 2% NaCl to the test water. The specimens for this test were moist cured for 2 weeks, then air dried for 1 week prior to testing.

6. The effectiveness in distributing electrical current.

   For this test, eight reinforced concrete slabs were fabricated as illustrated in Figure 1. After curing for at least 28 days, these slabs were continuously ponded with a 2% NaCl solution until the chloride content in each slab at the level of the top mat of rebars was at least 1.5 lb per yd^3 (as determined by chloride analysis conducted on concrete samples extracted from these slabs). Then, a Pt-Nb-Cu wire (0.031-in diameter) was installed along each end of each slab by casting cement paste around each wire on the slab.

   With each of the three conductive mixtures and the control mixture, 1.25-in thick overlays were cast over a pair of the reinforced slabs set aside for that mix. After the overlays had been properly cured for at least 28 days, a pair of 1.0-in wide holes were drilled through the overlay, at three different distances from either one of the two Pt-Nb-Cu wires in each slab (see Figures 1 and 2). These holes served as windows for the measurement of the half-cell potentials at these locations with a $Cu/CuSO_4$ electrode.

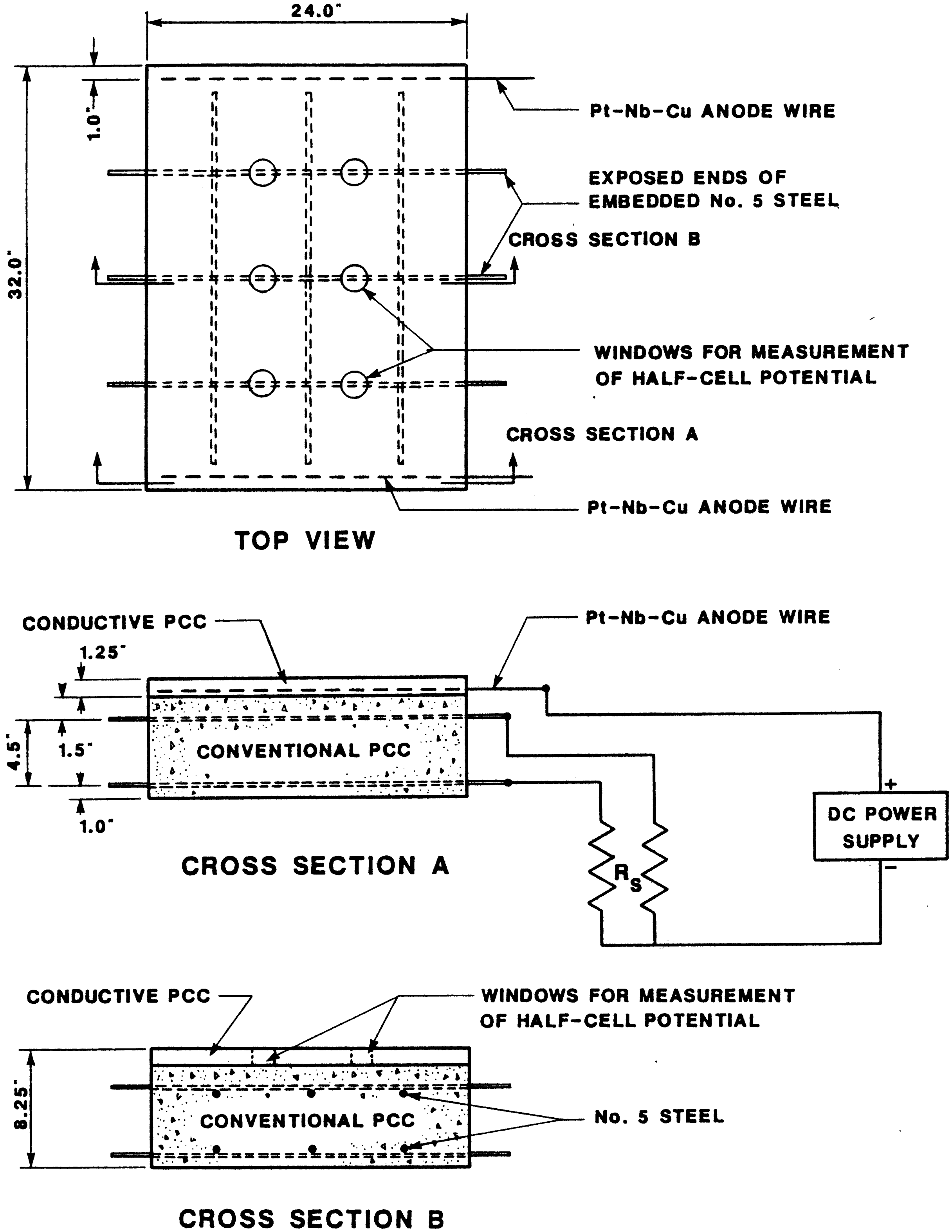

Figure 1. Setup of reinforced concrete slabs for testing the conductive PCC overlays under direct current.

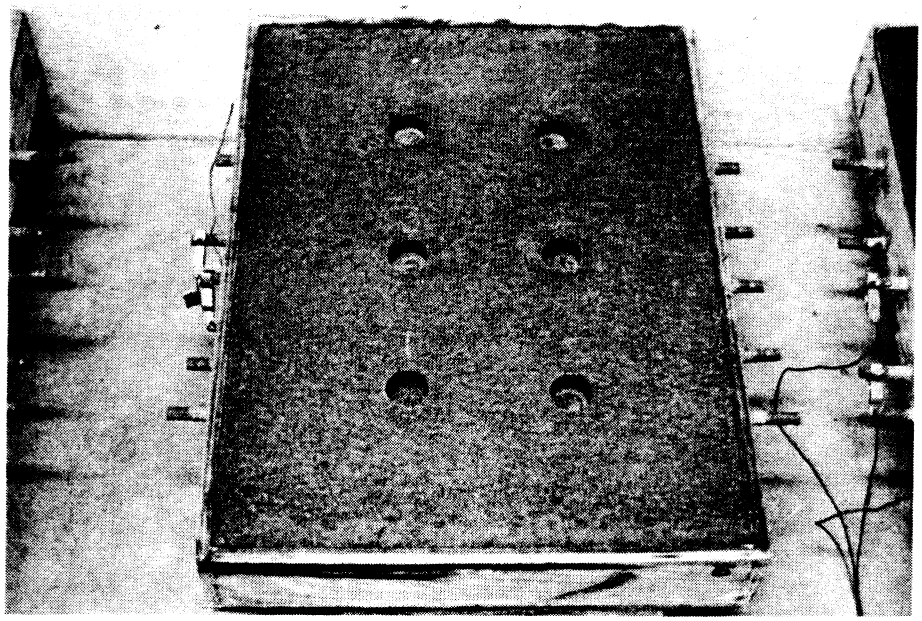

Figure 2. A reinforced concrete slab overlaid with conductive mix CFC-2. Notice the windows for measurement of half-cell potentials.

To test each mixture, a direct current was applied overnight to the two slabs that were overlaid with the mixture. Then, the current was turned off and the polarization on each slab at the three different distances from the Pt-Nb-Cu wire was determined by monitoring the decay or the half-cell potentials for 4 hours. This procedure was then repeated for several different applied voltages.

7. The effect of the current on bond strength.

In an attempt to assess this effect, a new test was devised. For this test, each shear specimen was embedded with a pair of electrodes made of stainless steel mesh: one in the base made of the control concrete mixture and the other in the overlay made of one of the conductive mixtures being tested. The procedure used for preparation of the specimens is described in Appendix A.

After each specimen had been properly cured, it was placed in a molded polycarbonate box (19-in long x 10.5-in wide x 8-in high). The specimen was covered with 10 liters of a 2% NaCl solution, before the positive terminal of a DC power supply was connected to the electrode embedded in the conductive mixture, and the negative terminal was connected to the remaining electrode (see Figures 3 and 4). Then, a direct current of 0.500 A at 5.00 volt was continuously applied through the specimen. Every 5 days a pair of the specimens was removed from the bath, rinsed, and sheared (as described in item 3) until the bonding surface in each specimen failed.

8. The effect of current on stability.

This effect was assessed by determining the change in weight of the specimens of each mixture as a result of the continuous application of a relatively high current through them.

Popsicle-shaped test specimens, such as that shown in the setup in Figure 5, were prepared from each mixture. After curing, each specimen was placed in a 400-ml beaker that was filled to the rim with a 2% NaCl solution and then connected to the positive terminal of a DC power supply (see Figure 6). The negative terminal of the power supply was connected to a Pt-Nb-Cu wire, which had a total length of 12 in, 9 in of which was immersed in the 2% NaCl solution. A DC current of 0.500 A at 5.00 volt was passed through the specimen for 5 days before the weight of the specimen was determined for comparison with the weight prior to the application of the current.

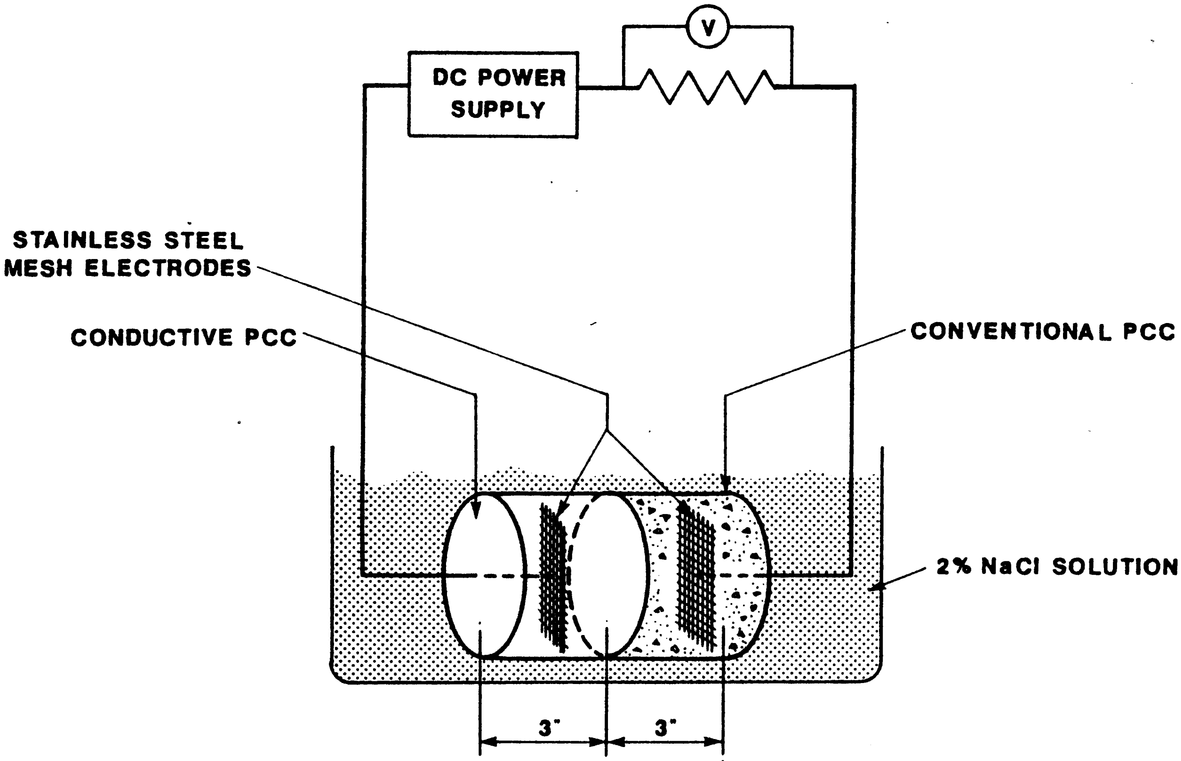

Figure 3. Setup for continuous application of current through a specimen to determine effect of current on the bond between a conductive concrete and a conventional concrete.

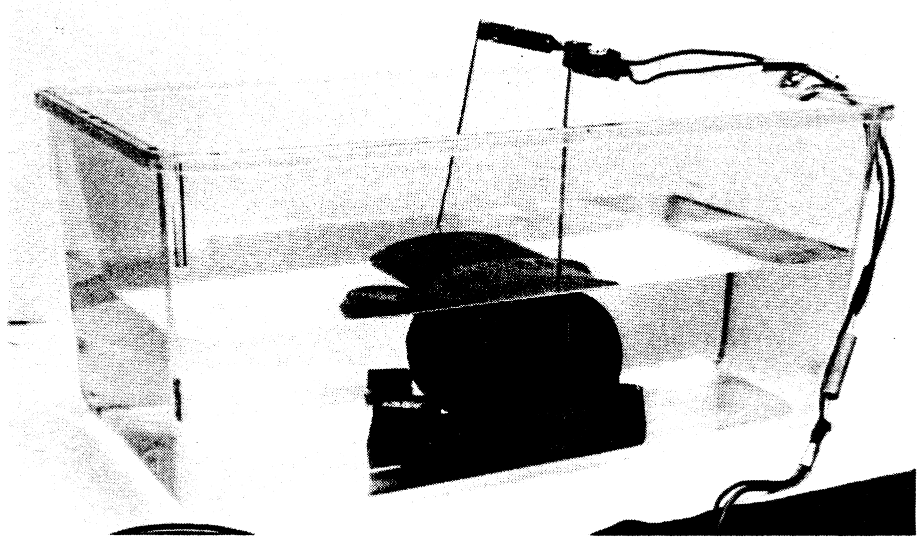

Figure 4. Application of current through a bond-strength specimen immersed in 2% NaCl solution.

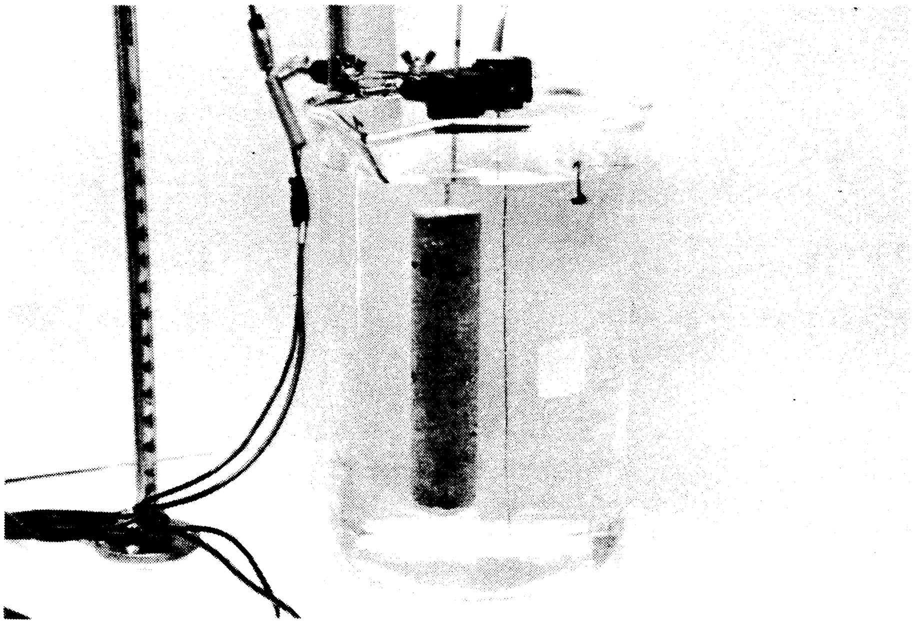

Figure 5. A popsicle anode made of a conductive concrete mix, immersed in a beaker of 2% NaCl solution, beside a Pt-Nb-Cu cathode.

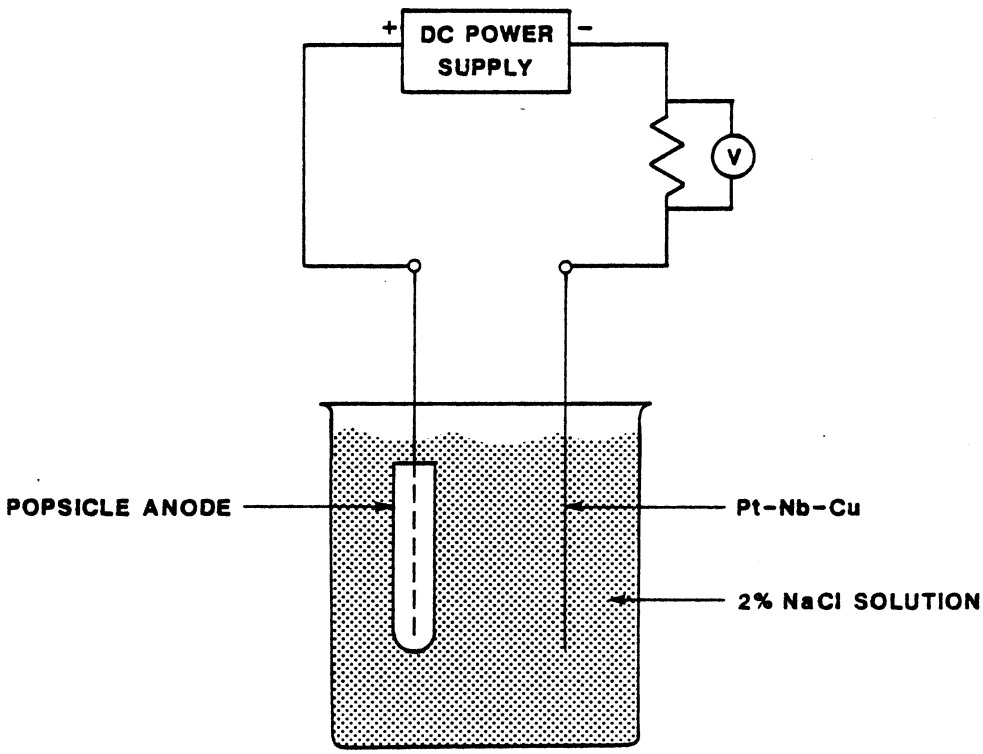

Figure 6. Setup for continuous application of current through a popsicle anode.

RESULTS AND DISCUSSION

Physical and Mechanical Properties

As was observed in the earlier investigation, these conductive concretes are relatively light, at least 10% lighter than the conventional portland cement concrete (see Table 1).

Table 2 shows some of the physical and mechanical characteristics of the three conductive concretes and the control. The electrical resistivities of these conductive concretes at 28 days varied between 143 to 163 ohm-cm, while the control was 1750 ohm-cm. And it appeared that the resistivities of these conductive concretes are consistent with the finding made in the earlier investigation that the resistivity of a conductive concrete is dependent on the combined concentration of not only the carbon fiber and carbon black but also the cement and water (1). This relationship, which is illustrated in Figure 7 that includes data for the four mixtures investigated earlier, may be used as guide in formulating mixtures with the desired resistivity.

Table 2

Resistivities and Mechanical Properties of
the Conductive Concrete

	Mixture			
	CF-4	CF-5	CFC-2	Control
Resistivity (ohm-cm)	163	156	143	1750
Compressive Strength (psi)	4070	5630	5490	5400
Tensile Strength (psi)	780	691	645	628
Bond Strength (psi)	760	706	630	550

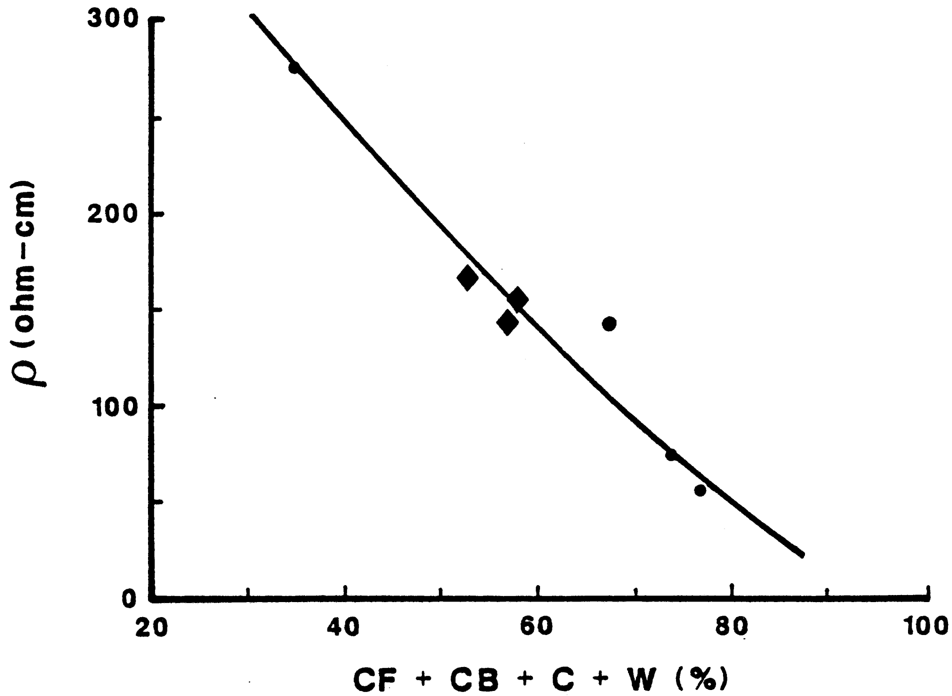

Figure 7. Influence of the combined concentration of carbon fiber, carbon black, cement, and water on resistivity.

It is difficult to define the effect of the carbon fiber alone on the compressive strength of these concretes. However, as illustrated in Figure 8, which again includes data from the previous four conductive mixtures and the control mixture, the fiber appeared to have a slight beneficial effect. Except for mixture CF-4, which had a relatively low compressive strength, the rest of the conductive mixtures appeared to have a higher compressive strength than the control. The low compressive strength of CF-4 is likely the result of its very high water-cement ratio, which was 0.60.

It appeared that carbon fiber had similar beneficial influence on the tensile strength of the conductive concrete, with the exception of the CFC-1 and CFC-2 mixtures (Figure 9). The inclusion of carbon black appeared to have caused these mixtures to behave differently from the other mixtures. Although the observed tensile strength of CFC-1 is at variance with that of CFC-2, it is likely that the carbon black particles may have behaved as a lubricant and adversely affected the cohesion and, therefore, the tensile strength of these concretes. This mechanism cannot be ignored when one later examines the bond strength of these conductive mixtures.

Again with the exception of CFC-1 and CFC-2, the bond strength of the other conductive concretes was enhanced by the presence of carbon fiber (Figure 10). These two mixtures exhibited consistently lower bond strengths than the rest, including the control mixture. It is apparent that the lubricating effect of the carbon black particles would have a similarly adverse influence on the adhesion of this type of concrete to a base concrete as it has on the cohesion of the concrete itself.

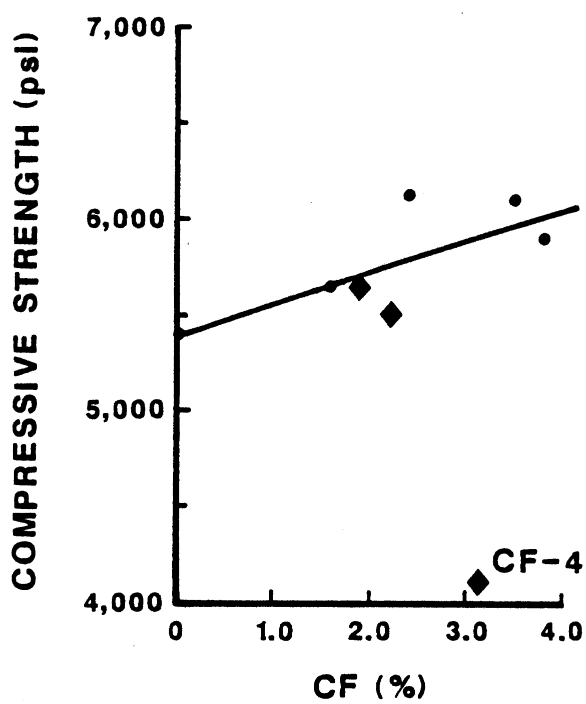

Figure 8. Influence of carbon fiber content on compressive strength.

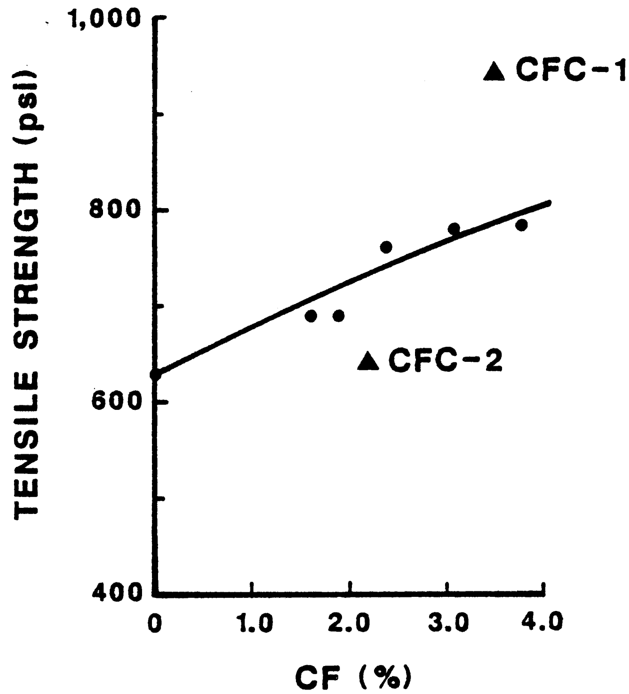

Figure 9. Influence of carbon fiber content on tensile strength.

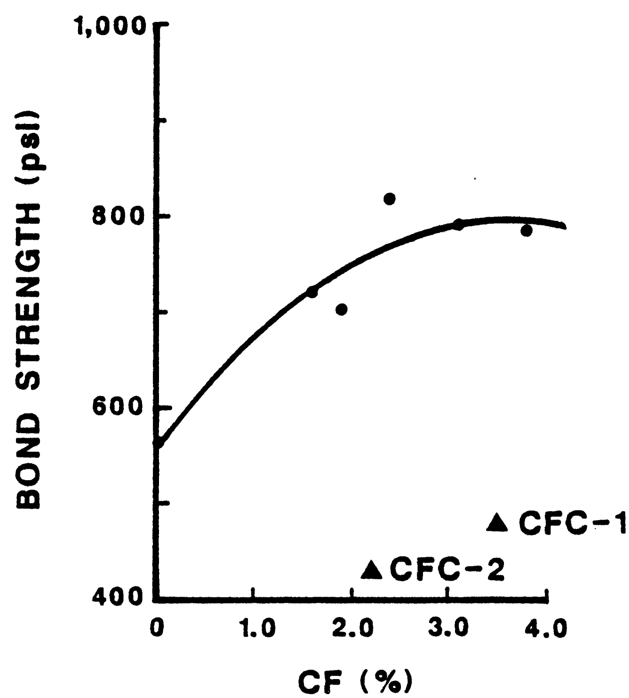

Figure 10. Influence of carbon fiber content on bond strength.

When the three conductive concretes and the control were subjected to varied numbers of cycles of change in the ambient air temperature from 0°F to 100°F, there appeared to be some loss in bond strength. As shown in Figure 11, after 200 cycles, the loss ranged from approximately 29% to 39% for the conductive concretes. For the control, the loss was approximately 24%. However, the final bond strengths of the three conductive concretes, which ranged from 430 to 512 psi, were at least comparable with that of the control, which was approximately 430 psi. It is interesting to note that in all cases, most of the losses in the bond strength occurred within the first 100 cycles (see Figure 11).

In Virginia, the criteria for the freeze-thaw resistance of a concrete require that for satisfactory performance at 300 cycles, the average weight loss be < 7% and the durability factor be > 60. As Table 3 indicates, only CF-5 gave any indication that it will likely perform satisfactorily. The CF-4 failed after only 190 cycles, whereas CFC-2 failed after 240 cycles. There is no doubt that the poor performance of these two concretes resulted from their too high water-cement ratios combined with insufficient air content, especially for CF-4 (see Table 1). In contrast, CF-5 had a desirable water-cement ratio and an air content that was at least adequate.

Table 3

Freeze-Thaw Resistance of the Conductive Concrete

Mix	Weight Loss (%)	Durability Factor
CF-4	17	47
CF-5	3	70
CFC-2	10	57

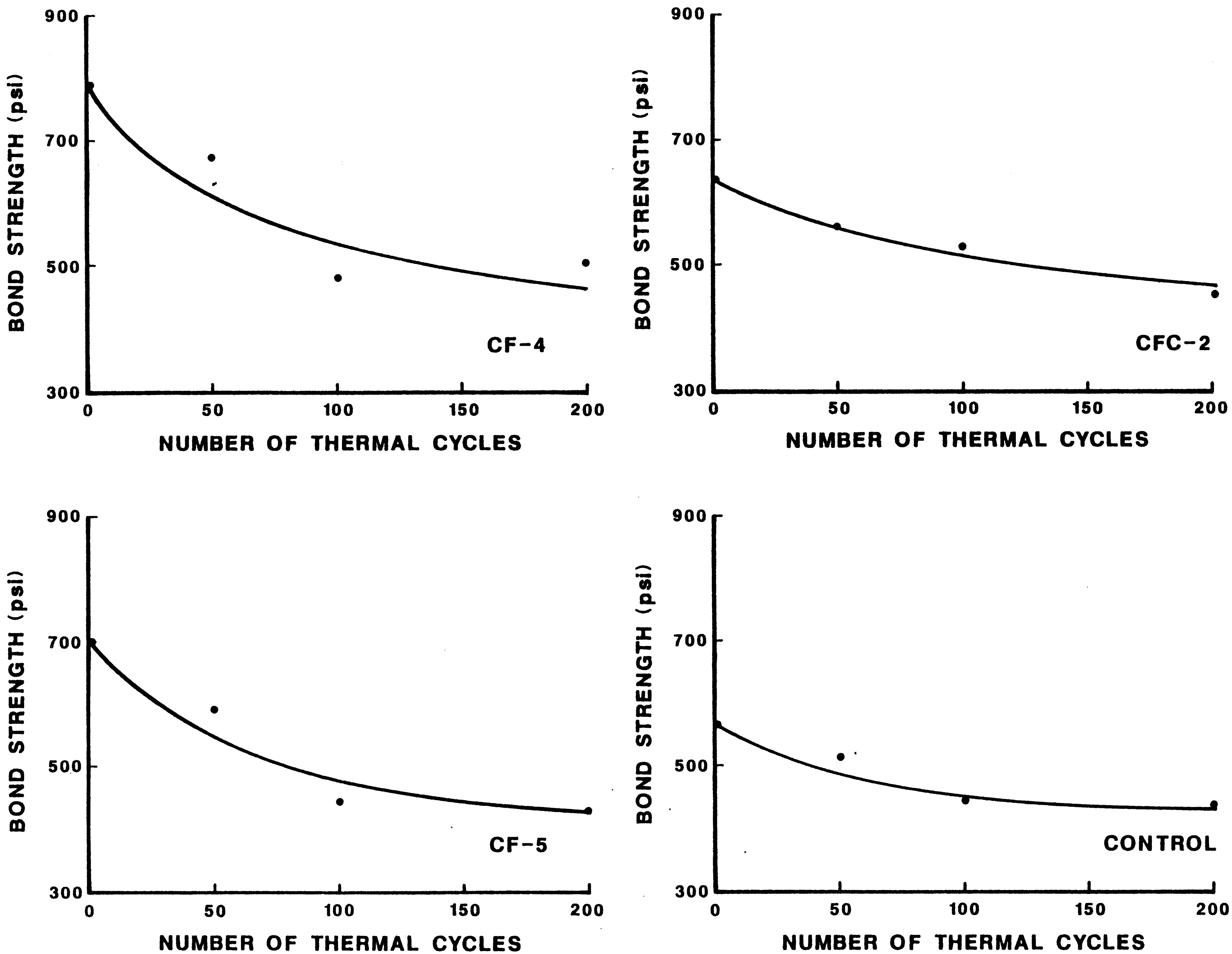

Figure 11. Effect of thermal cycles on the bond strength of the conductive concrete mixes and control.

Electrical Properties

Distribution of Current

A constant direct current of 20 mA was applied at several different voltages to one of the pair of Pt-Nb-Cu anodes installed at the ends of each of the eight reinforced concrete slabs described earlier. The current was equivalent to approximately 9.4 mA per square foot of reinforcing steel. Appendix B presents the different degrees of polarization that were attained on each slab at the three different distances from the anode as a result of the distribution of the applied current across the slab by the particular overlay used. A plot of the average polarization attained through each of the three conductive overlays and the control overlay as a function of distance from the anode and applied voltage is shown in Figure 12.

As illustrated in the slabs with the control overlay, the degree of polarization that was achieved decreased very rapidly with increasing distance from the anode. Since higher applied voltage yielded a higher degree of polarization, the rate of decrease in polarization with distance appeared to be most rapid at higher voltage and converged at approximately 22 in for the control overlay. In contrast, the rates of decrease in polarization with increasing distance from an anode were significantly lower for the slabs with the conductive overlays. This therefore indicates that the current can be distributed on a reinforced concrete bridge deck further away from the source (the Pt-Nb-Cu anode) with either of the three conductive overlays than with the control overlay.

By extrapolation from the various relationships presented in Figure 12, the maximum distance at which a minimum polarization of 100 mV can be attained as a function of the applied voltage can be estimated for each type of overlay (see Figure 13). As might have been predicted, with the control overlay, the maximum distance from the anode within which the desired 100-mV polarization (a widely accepted criterion for an effective CP system) can still be achieved is approximately 22 in for all voltages. With each of the conductive overlays, the maximum distance appeared to be dependent on the applied voltage, with the peak located between 4 and 5V. The CF-5 overlay showed the highest distribution, which was approximately 132 in at the peak. It was followed by CFC-2 at 129 in and CF-4 at 116 in. This implies that with any of these conductive overlays on a bridge deck, it would require no more than one anode wire installed on each traffic lane for an effective distribution of the CP current.

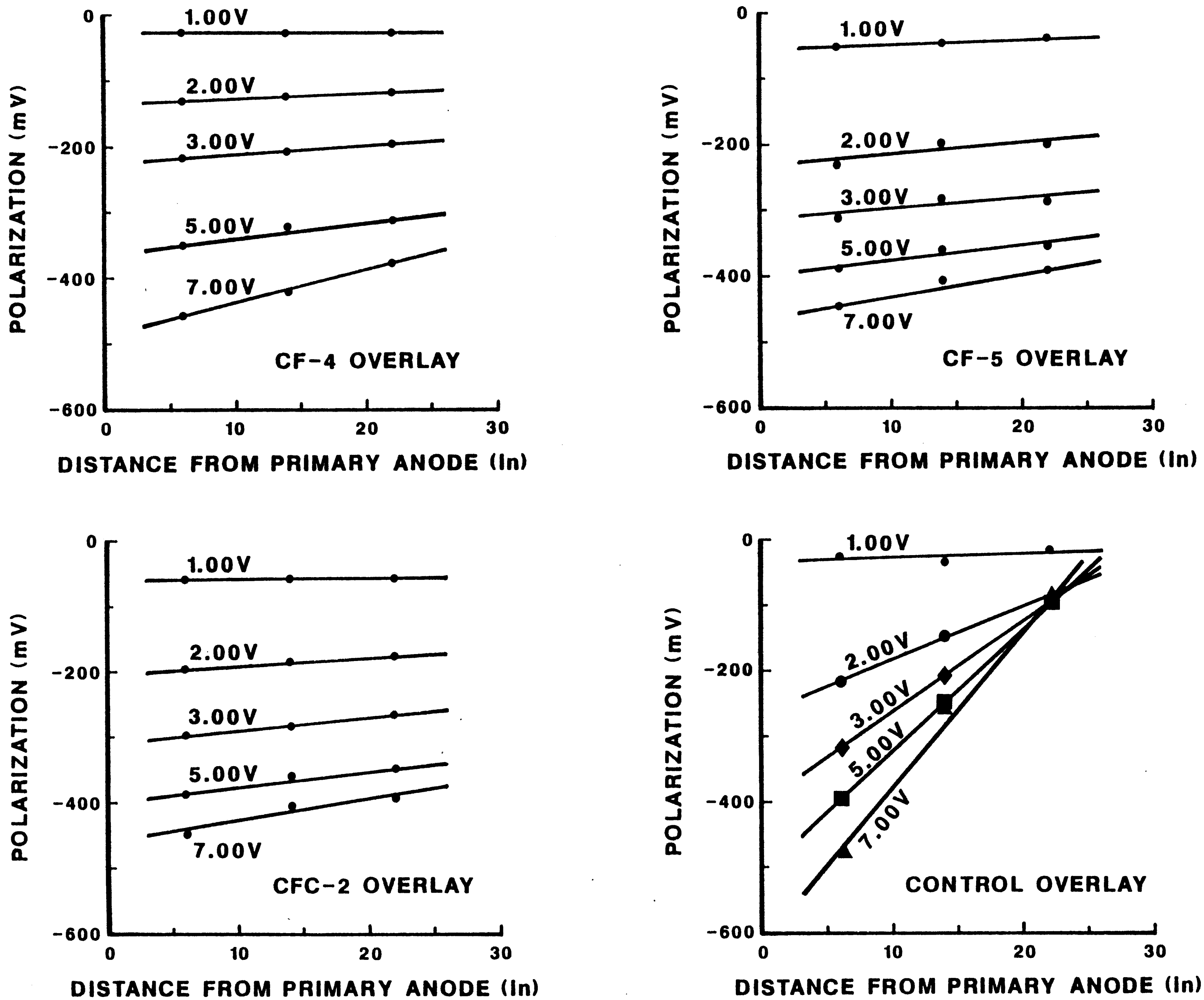

Figure 12. Polarization at various distances from a Pt-Nb-Cu primary anode and applied voltage, for three conductive overlays and a control overlay.

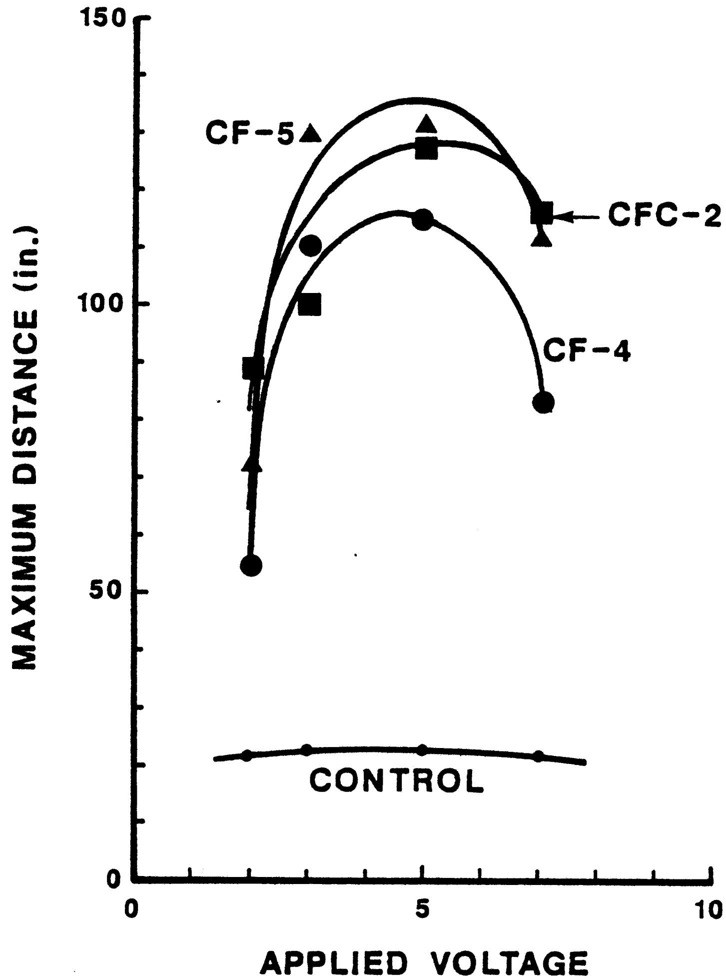

Figure 13. Maximum distance from a Pt-Nb-Cu anode at which polarization was > 100 mV, as a function of applied voltage, for various overlays.

Accordingly, it was expected that more current would reach the rebars (at least those in the top mat) in those slabs overlaid with the conductive concretes than those in the slabs overlaid with the less conductive control concrete. An examination of the measured current that was received by the top-mat rebars of each of the test slabs (see Appendix C and Figure 14) shows that the conductivity of the overlay used did influence the distribution of current, not only laterally along the surface of a concrete slab, but also through the depth of the slab. The quantity of current reaching the top-mat rebars in the test slabs appeared to be highest in CF-5, with CFC-2, CF-4, and the Control next (in descending order).

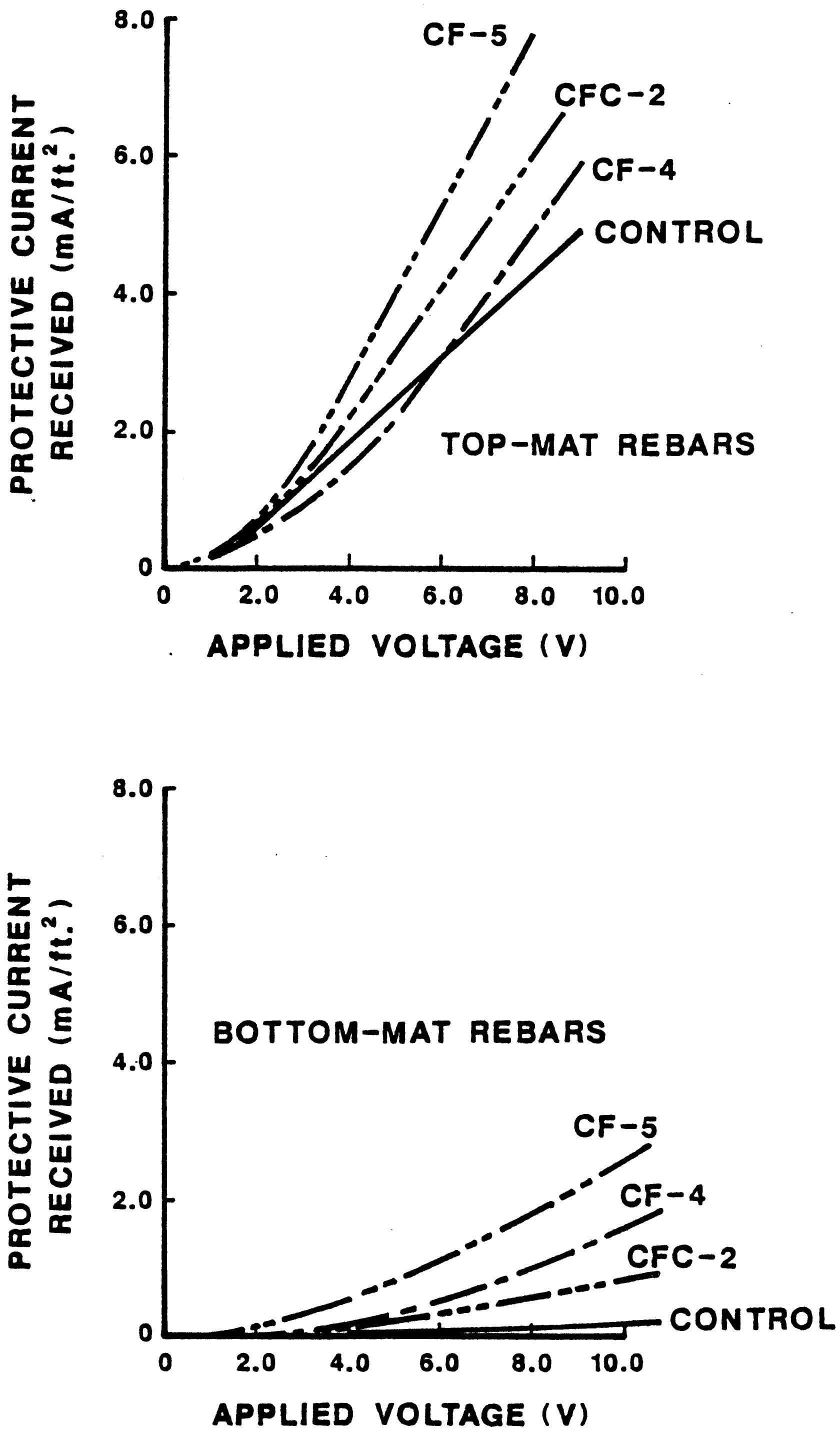

Figure 14. Protective current received by rebars in test concrete slabs with different overlays, as a function of applied DC voltage.

As expected the current received by the bottom mat of rebars in each slab was less than the amount received by the top mat and appeared to be highest in CF-5, with CF-4, CFC-2, and the Control next (in descending order). It is unclear why more current had reached the bottom-mat rebars in the slabs overlaid with CF-4 than in the slabs with the CFC-2 overlay. Nevertheless, the results also clearly showed the beneficial influence of the conductive overlay on the distribution of CP current to even the bottommat rebars.

Estimates of the effective "combined resistance" of each of the overlays tested can be made from the slopes of the various relationships between applied voltage and current received shown in Figure 14. These estimates, which are presented in Table 4, provide an indication of the magnitude of the combined resistance of the overlay, the bonding surface between the overlay and the base concrete, and the layer of base concrete above the top mat of rebars or the bottom mat of rebars, whichever is the case.

It is interesting to note that for the control slabs, which had a conventional concrete overlay with resistivity at least 10 times that of the three conductive overlays, the estimated average "combined resistance" of 1630 ohm per sq ft wasn't proportionately larger than those for the slabs with the conductive overlays (810 to 1230 ohm per sq ft). This perhaps is an indication that the electrical resistance due to the bonding surface between the overlay and the base concrete may also be relatively important in the overall distribution of protective current from the anodes to the rebars and may serve as another focal point for improving cathodic protection systems that utilize overlays.

Table 4

Combined Resistance Between the Overlay and the Rebars

Overlay	Resistance (ohm-sq ft) Top Mat	Resistance (ohm-sq ft) Bottom Mat
CF-4	1230	6240
CF-5	810	3540
CFC-2	1000	10800
Control	1630	49200

Effect of Current on Bond Strength

Since it is envisioned that the conductive concrete would be applied as a layer on an existing reinforced concrete structure to facilitate the distribution of electrical current across the structure, it is absolutely necessary that the current not have an adverse effect on the ability of the conductive concrete to remain bonded to the base concrete.

As mentioned earlier, a new test was devised to assess this possible effect. In this test, shear specimens that were embedded with electrodes were submerged in a 2.0% NaCl solution and subjected to a continuous direct current of 500 mA at 5.00 V before being sheared at the bonding surface between the conductive concrete and the conventional concrete at 5-day intervals. This current is equivalent to about 5730 mA per sq ft of concrete, or about 3820 times the typical current density of about 1 to 2 mA per sq ft that is needed to achieve sufficient polarization in most reinforced concrete structures. Therefore, the total amount of current applied to each shear specimen in a 5-day interval is equivalent to the accumulated current that would normally be applied to a concrete structure in about 50 years.

The results of this test, which are illustrated in Figure 15, appear to indicate that the continuous flow of electricity from the conductive concrete to the base concrete through their bonding surface had actually slightly improved, instead of degraded, the bond. The clue to this unexpected beneficial effect of the current, which was in contrast to the adverse effect in the thermal-cycles test, may lie in the appearance of white crystalline material on the outer surface of the conductive-concrete half of the specimens (see Figure 16). The quantity of this crystalline material, which was also visible in traces on the bonding surfaces of the specimens after they had been sheared to failure, appeared to increase with the duration of current. It is believed that the crystalline material that had formed in the accessible pores in each specimen from migrating ions in the solution during the flow of current had strengthened the bonding surface by serving as anchors.

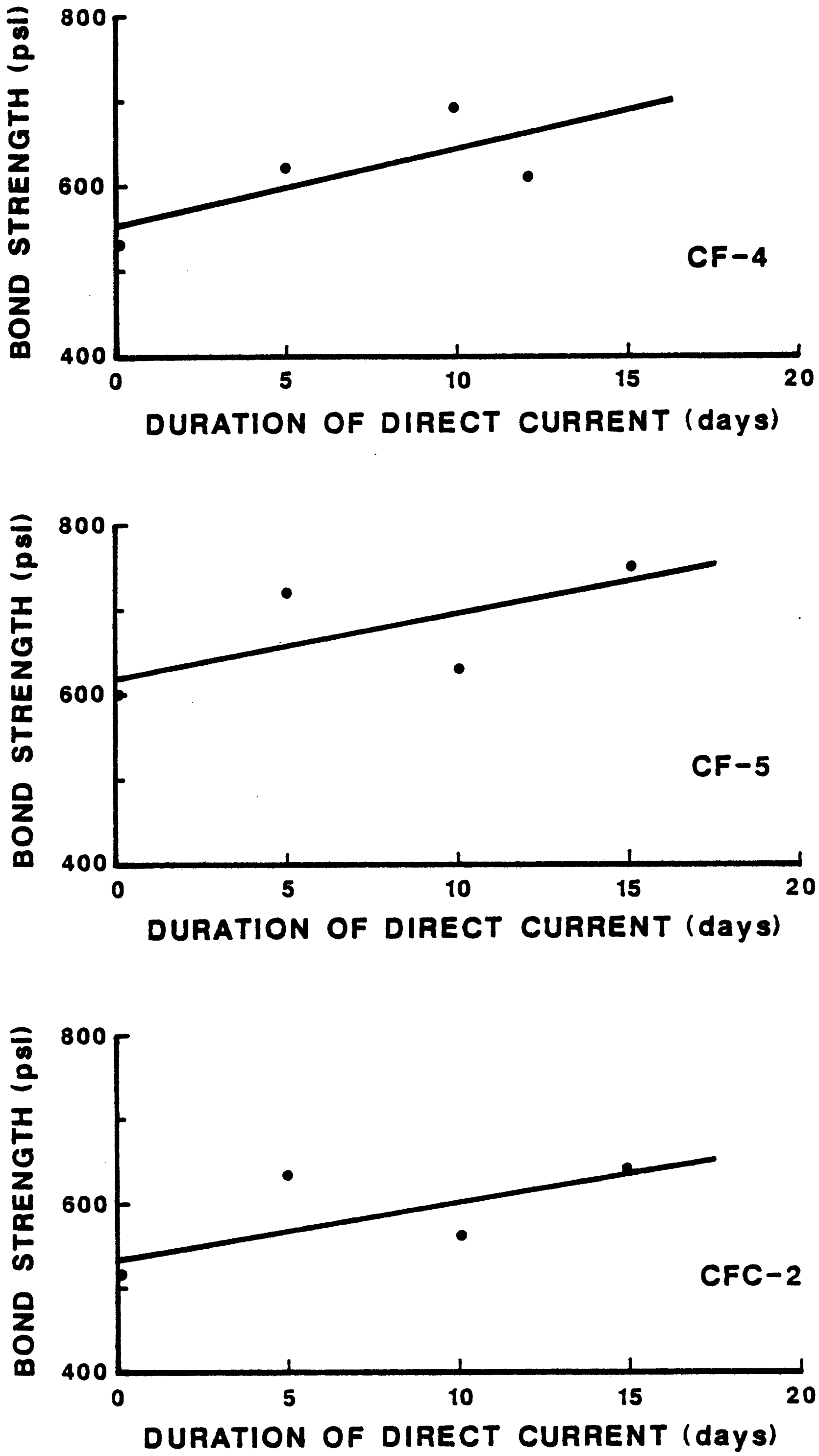

Figure 15. Effect of current on the ability of the conductive concrete to remain bonded to a base concrete.

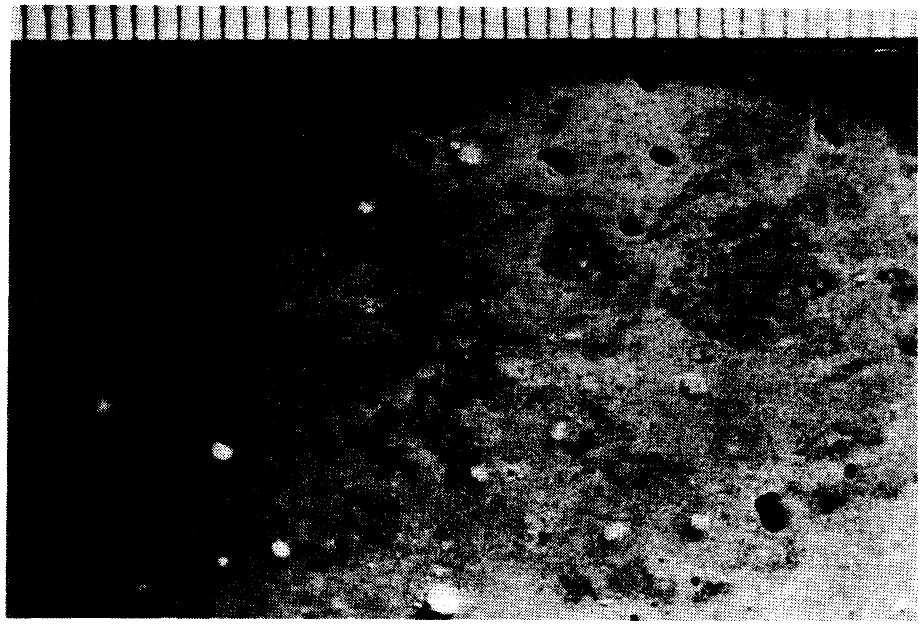

Figure 16. White crystalline substances that formed on the shear specimens after passage of current.

Effect of Current on Stability of the Conductive Concrete

As in the test used to assess the possible effect of current on bond strength, the test to assess the possible effect of current on the stability of the conductive concretes was similarly accelerated. A direct current of 500 mA was passed through each popsicle test specimen, which had a total outer surface area of approximately 0.153 sq ft, for 5 days. This amount of current is equivalent to applying a typical 1 to 2 mA per sq ft of current to a concrete structure for at least 30 years. However, it must be emphasized that as with many other accelerated tests, there is a suspicion that the extremely high current used to accelerate the effect so that it could be observed within the time frame of the test may indeed cause deterioration of the material in a short time that otherwise would not occur if the test current were at the typically low working level, even for a long period of time.

As indicated by the results tabulated in Table 5, there were slight losses of material from the specimens, except those of CF-5. The losses in weight ranged from a low of 0.19% for the control, to a high of 1.87%

for CF-4. This loss in material was likely the result of a net excess in the migration of ions from the specimens over the migration of ions from the solution to the specimens. The opposite may have occurred in the case of CF-5, as evidenced by the formation of much small crystalline material around the specimens. This crystalline material is likely identical to that observed in the specimens used in the test on the effect of current on bond strength.

In the test for freeze-thaw resistance, one of the criteria for acceptance is loss in weight of < 7%. If this is also used as a criterion for this test, then the changes in weights exhibited by the conductive concretes in this test have to be considered at least acceptable.

Table 5

Effect of Extremely High Level of Current on the Weight of the Conductive Concrete

Mix	Specimen	Weight (gm) Before	Weight (gm) After	Change in Weight (%)	Average
CF-4	a	124.70	122.40	-1.84	-1.87
	b	125.43	123.04	-1.91	
CF-5	a	160.20	160.30	0.06	0.28
	b	161.65	162.47	0.51	
CFC-2	a	165.28	164.50	-0.47	-0.25
	b	165.66	165.60	-0.04	
Control	a	256.47	256.10	-0.14	-0.19
	b	259.52	258.90	-0.24	

CONCLUSIONS

Based on the results presented, the following conclusions can be made:

1. The addition of carbon fiber, alone or in combination with carbon black, can yield portland cement concrete that is relatively more electrically conductive and lighter than conventional concrete. Some mechanical properties of such conductive concrete would at least be comparable to, if not better than, those of conventional concrete.

2. As would be expected even with conventional concrete, the conductive concretes with an excessive water-cement ratio and insufficient air content in their mixture designs showed poor freeze-thaw resistance.

3. Accelerated thermal cycles appeared to degrade the bond strength of the conductive concretes. However, such degradation was also observed in the control. Furthermore, the final bond strengths of the conductive concretes after 200 thermal cycles appeared to be at least comparable to that of the control.

4. When used as overlays on a reinforced concrete structure, the conductive concretes tested appeared to have sufficient conductivity to facilitate the distribution of protective current over a larger area on the structure than an overlay of conventional concrete. In addition, the amount of current reaching the reinforcing steel appeared to have increased when the structure was overlaid with any of the conductive concretes tested.

5. Using a new accelerated test devised for this study, it was determined that the continuous flow of current from any of the conductive concretes to a conventional concrete didn't have any adverse effect on the ability of the conductive concrete to remain bonded to a base concrete. On the contrary, the results appeared to indicate that the current may actually enhance the bond.

6. Extended flow of current through the conductive concrete may eventually affect the material. However, it is doubtful that the relatively small effect would have any adverse effect on the service life of this material as an overlay on a bridge deck.

7. Based on the overall properties of the three conductive concrete mixtures tested, it is believed that a mixture similar to CF-5 (see Table 1) would be sufficiently conductive and durable to warrant further testing on an existing bridge deck.

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APPENDIX A

SPECIMEN FOR TEST OF THE EFFECT OF CURRENT ON BOND STRENGTH

The following describe the procedure used to prepare the specimens:

1. Shorten the 4 in (D) x 8 in (H) cylindrical mold used for making cylindrical concrete specimens to a height of 5 in.

2. Solder a 10-in No. 14 AWG insulated copper wire to the center of a No. 2 stainless steel mesh made of 0.120-in diameter wires and measures 2 in x 2 in. This assembly will serve as an electrode, two of which are needed for each specimen.

3. Punch a hole in the bottom of the mold. This hole should be slightly smaller than the diameter of the No. 14 AWG cooper wire, which is approximately 0.125 in.

4. From the inside of the mold, insert the unconnected copper end of an electrode assembly through the hole. Bend the end of the copper wire to prevent the assembly from slipping back out of the mold, as shown in Figure A-1.

5. Holding the mesh end, lightly pull the assembly out of the mold as far as it will go. Then pour enough fresh class A4 concrete (2) into the mold to form a 1.25-in layer. Place the mold on a vibrating table set for moderate vibration rate and vibrate for 15 seconds to consolidate the concrete.

6. Pull the end of the copper wire to let the mesh rest on this layer of concrete.

7. Pour another 1.25-in layer of the fresh concrete over the mesh and vibrate for another 15 seconds. Let this concrete cure for 28 days in a moisture room.

8. Pour a 1.25-in layer of a freshly mixed conductive concrete on one of the cured based concretes and vibrate similarly.

9. Let the mesh of another electrode assembly rest on the center of this first layer of the conductive concrete to be tested.

10. Pour a second 1.25-in layer of the fresh conductive concrete over the mesh, making sure that the mesh stays centered in the mold. Vibrate similarly. Then cure for 28 days in the moisture room before testing.

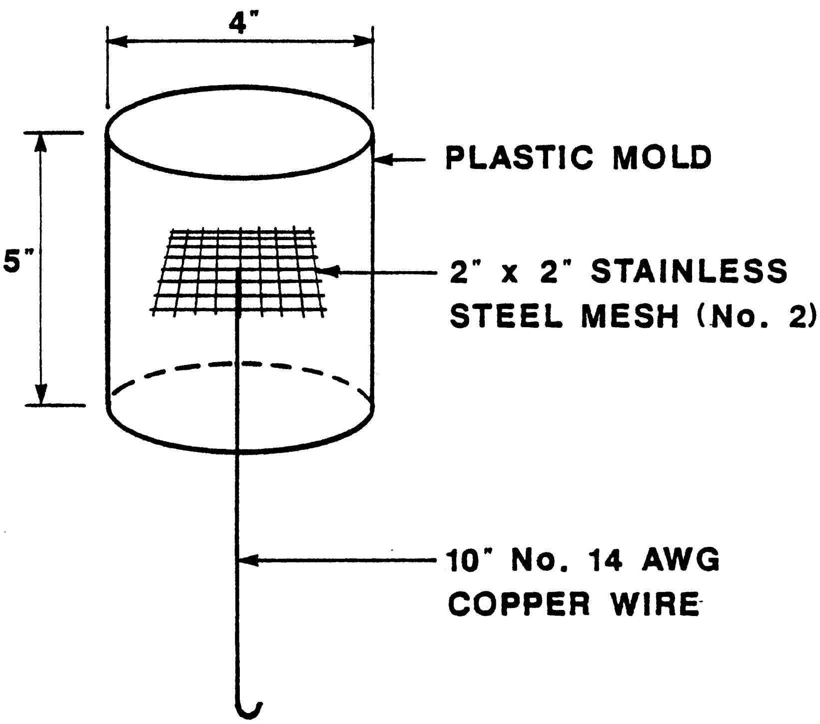

Figure A-1. Plastic mold and a mesh electrode used in making shear specimens.

APPENDIX B

POLARIZATION ATTAINED AT VARIOUS DISTANCES FROM A PRIMARY ANODE

Overlay	Slab	System Voltage (V)	System Current (A)	Polarization (mV) at 6.0 in	Polarization (mV) at 14.0 in	Polarization (mV) at 22.0 in	Avg Polarization (mV) at 6.0 in	Avg Polarization (mV) at 14.0 in	Avg Polarization (mV) at 22.0 in
CF-4	a	0.00	0.020	0	0	0	0	0	0
		1.00	0.020	- 15	- 20	- 10	- 28	- 28	- 28
		2.00	0.020	- 70	- 65	- 55	-130	-125	-120
		3.00	0.020	-165	-145	-135	-218	-205	-200
		5.00	0.020	-320	-305	-275	-350	-335	-313
		7.00	0.020	-435	-400	-350	-455	-423	-380
	b	0.00	0.020	0	0	0			
		1.00	0.020	- 40	- 35	- 45			
		2.00	0.020	-190	-185	-185			
		3.00	0.020	-270	-265	-265			
		5.00	0.020	-380	-365	-350			
		7.00	0.020	-475	-445	-410			
CF-5	a	0.00	0.020	0	0	0	0	0	0
		1.00	0.020	- 60	- 50	- 45	- 53	- 45	- 43
		2.00	0.020	-280	-255	-255	-230	-198	-200
		3.00	0.020	-390	-365	-365	-310	-283	-283
		5.00	0.020	-480	-455	-455	-390	-363	-353
		7.00	0.020	-550	-505	-510	-455	-410	-403
	b	0.00	0.020	0	0	0			
		1.00	0.020	- 45	- 40	- 40			
		2.00	0.020	-180	-140	-145			
		3.00	0.020	-230	-200	-200			
		5.00	0.020	-300	-270	-250			
CFC-2	a	0.00	0.020	0	0	0	0	0	0
		1.00	0.020	- 70	- 60	- 75	- 60	- 55	- 55
		2.00	0.020	-210	-185	-200	-203	-193	-183
		3.00	0.020	-300	-275	-275	-303	-285	-268
		5.00	0.020	-350	-330	-330	-388	-363	-350
		7.00	0.020	-400	-380	-385	-443	-405	-393
	b	0.00	0.020	0	0	0			
		1.00	0.020	- 50	- 50	- 35			
		2.00	0.020	-195	-200	-165			
		3.00	0.020	-305	-295	-260			
		5.00	0.020	-425	-395	-370			
		7.00	0.020	-485	-430	-400			

Polarization Attained at Various Distances From a Primary Anode (continued)

Overlay	Slab	System Voltage (V)	System Current (A)	Polarization (mV) at 6.0 in	Polarization (mV) at 14.0 in	Polarization (mV) at 22.0 in	Avg Polarization (mV) at 6.0 in	Avg Polarization (mV) at 14.0 in	Avg Polarization (mV) at 22.0 in
Typical Concrete	a	0.00	0.020	0	0	0	0	0	0
		1.00	0.020	- 10	- 25	- 10	- 25	- 40	- 25
		2.00	0.020	-180	-130	- 80	-220	-150	- 95
		3.00	0.020	-275	-180	- 80	-310	-205	-105
		5.00	0.020	-365	-225	- 75	-400	-250	-105
		7.00	0.020	-445	-220	- 85	-470	-250	- 95
	b	0.00	0.020	0	0	0			
		1.00	0.020	- 40	- 55	- 40			
		2.00	0.020	-260	-170	-110			
		3.00	0.020	-345	-230	-130			
		5.00	0.020	-435	-275	-135			
		7.00	0.020	-495	-280	-105			

APPENDIX C

Current Reaching Various Mats of Rebars in the Test Slabs

Overlay	Slab	Voltage (V)	Current (A)	Current (mA/sq. ft.) Top Mat	Current (mA/sq. ft.) Bottom Mat	Average Current Top Mat	Average Current Bottom Mat
CF-4	a	0.00	0.020	0.00	0.00	0.00	0.00
		1.00	0.020	0.00	0.00	0.06	0.00
		2.00	0.020	0.11	0.00	0.28	0.06
		3.00	0.020	0.45	0.11	0.62	0.11
		5.00	0.020	2.49	0.34	2.26	0.40
		7.00	0.020	4.86	0.68	4.24	0.85
	b	0.00	0.020	0.00	0.00		
		1.00	0.020	0.11	0.00		
		2.00	0.020	0.45	0.11		
		3.00	0.020	0.79	0.11		
		5.00	0.020	2.04	0.45		
		7.00	0.020	3.62	1.02		
CF-5	a	0.00	0.020	0.00	0.00	0.00	0.00
		1.00	0.020	0.16	0.03	0.11	0.02
		2.00	0.020	0.27	0.06	0.51	0.09
		3.00	0.020	1.33	0.27	1.54	0.29
		5.00	0.020	3.93	0.86	4.01	0.85
		7.00	0.020	6.79	1.59	6.64	1.49
	b	0.00	0.020	0.00	0.00		
		1.00	0.020	0.06	0.01		
		2.00	0.020	0.74	0.12		
		3.00	0.020	1.76	0.31		
		5.00	0.020	4.10	0.84		
		7.00	0.020	6.49	1.39		
CFC-2	a	0.00	0.020	0.00	0.00	0.00	0.00
		1.00	0.020	0.07	0.01	0.10	0.01
		2.00	0.020	0.86	0.10	0.51	0.06
		3.00	0.020	1.80	0.22	1.21	0.12
		5.00	0.020	4.16	0.48	2.94	0.29
		7.00	0.020	6.83	0.76	5.50	0.52
	b	0.00	0.020	0.00	0.00		
		1.00	0.020	0.13	0.01		
		2.00	0.020	0.16	0.01		
		3.00	0.020	0.62	0.03		
		5.00	0.020	1.72	0.09		
		7.00	0.020	4.16	0.28		

Current Reaching Various Mats of Rebars in the Test Slabs (continued)

				Current (mA/sq. ft.)		Average Current	
Overlay	Slab	Voltage (V)	Current (A)	Top Mat	Bottom Mat	Top Mat	Bottom Mat
Typical Concrete	a	0.00	0.020	0.00	0.00	0.00	0.00
		1.00	0.020	0.10	0.00	0.11	0.00
		2.00	0.020	0.51	0.00	0.57	0.00
		3.00	0.020	0.96	0.11	1.15	0.09
		5.00	0.020	2.55	0.11	2.36	0.11
		7.00	0.020	3.56	0.11	3.63	0.12
	b	0.00	0.020	0.00	0.00		
		1.00	0.020	0.12	0.00		
		2.00	0.020	0.63	0.00		
		3.00	0.020	1.34	0.07		
		5.00	0.020	2.16	0.11		
		7.00	0.020	3.70	0.13		