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16. Abstract There is a need for an effective, simple-to-install secondary anode system for use in the cathodic protection of reinforced concrete bridge decks. In pursuit of such a system, carbon fibers and carbon black were incorporated in portland cement concrete in an attempt to improve its electrical conductivity. It was found that carbon fibers alone or in combination with carbon black considerably improved the electrical conductivity without sacrificing the desirable mechanical properties of the conventional concrete. Potentially, such a concrete could be used as an overlay on a repaired deck to act as a secondary anode to effectively spread the protective current of a cathodic protective system over the entire deck, and thereby simplify the installation problem.					
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ELECTRICALLY CONDUCTIVE PORTLAND CEMENT CONCRETE

by

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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

There is a need for an effective, simple-to-install secondary anode system for use in the cathodic protection of reinforced concrete bridge decks. In pursuit of such a system, carbon fibers and carbon black were incorporated in portland cement concrete in an attempt to improve its electrical conductivity. It was found that carbon fibers alone or in combination with carbon black considerably improved the electrical conductivity without sacrificing the desirable mechanical properties of the conventional concrete. Potentially, such a concrete could be used as an overlay on a repaired deck to act as a secondary anode to effectively spread the protective current of a cathodic protective system over the entire deck, and thereby simplify the installation problem.

CONVERSION FACTORS

To Convert From	To	Multiply By
in	cm	2.54
in	mm	25.4
lb/ft ³	Kg/m ³	16.0185
psi	MPa	6.8948 E-03

$$^{\circ}\text{C} = \frac{(^{\circ}\text{F} - 32)5}{9}$$

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INTRODUCTION

Impressed-current cathodic protection (CP) is, in general, proving to be an effective means of arresting the corrosion of the rebars in bridge decks in service and thereby preventing premature failure of the decks. Since concrete is a poor electrical conductor, the anodes in the CP system must be spaced very close to each other to achieve an even distribution of the applied current. In the latest version of a CP system for bridge decks, called the slotted-anode system, the graphite-strand anodes are laid in slots cut into the concrete surface of a deck and spaced no more than 1 ft apart (Figures 1 and 2). And since the installation of these closely spaced anodes requires relatively labor-intensive operations, the installation cost has been high.

To simplify installation, the industry has introduced two different anode systems, both of which come in mesh. One is fabricated from copper wires coated with a proprietary conductive polymer, and the other is made of titanium having a catalytic coating. The installation of each system involves unrolling and tacking down the mesh over a prepared deck and topping the entire deck with an overlay of portland cement concrete (PCC). These two alternative systems have eliminated the need for cutting slots into the surface of a deck; however, they do not provide any significant reduction in installation labor.

The preceding discussion suggests that there is still a need to develop simpler alternatives. A potential alternative may be found if the resistivity of portland cement concrete could be significantly decreased. As illustrated in Figures 3 and 4, the resulting conductive concrete could then be used as a combined anode-overlay system following the preparation of a deck and the installation of a sufficient number of primary anodes, and could thereby considerably simplify the installation procedure.

This report describes an exploration of the use of electrically conductive additives to lower the resistivity of a typical PCC without sacrifice of the desirable mechanical properties of the concrete.

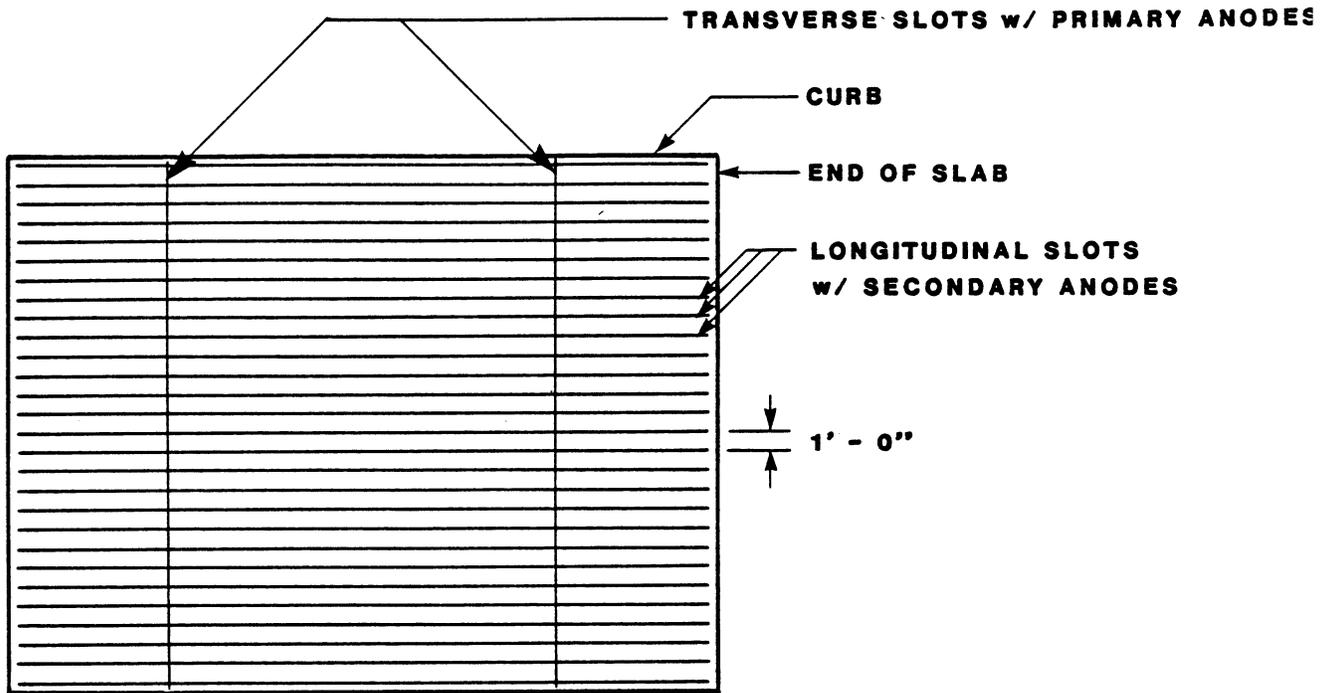


Figure 1. Typical top view plan of a CP system utilizing a grid of anodes embedded in slots sawed into the concrete surface of a deck.

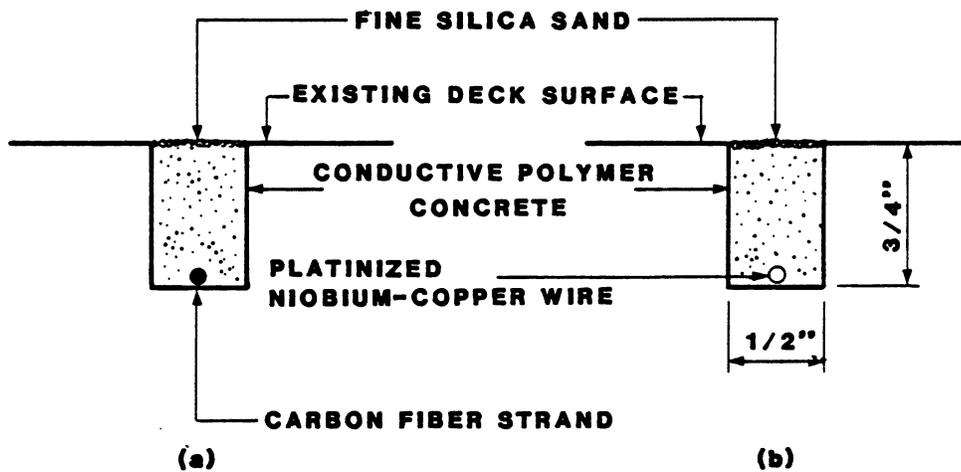


Figure 2. Cross-sectional views showing (a) transverse and (b) longitudinal slots.

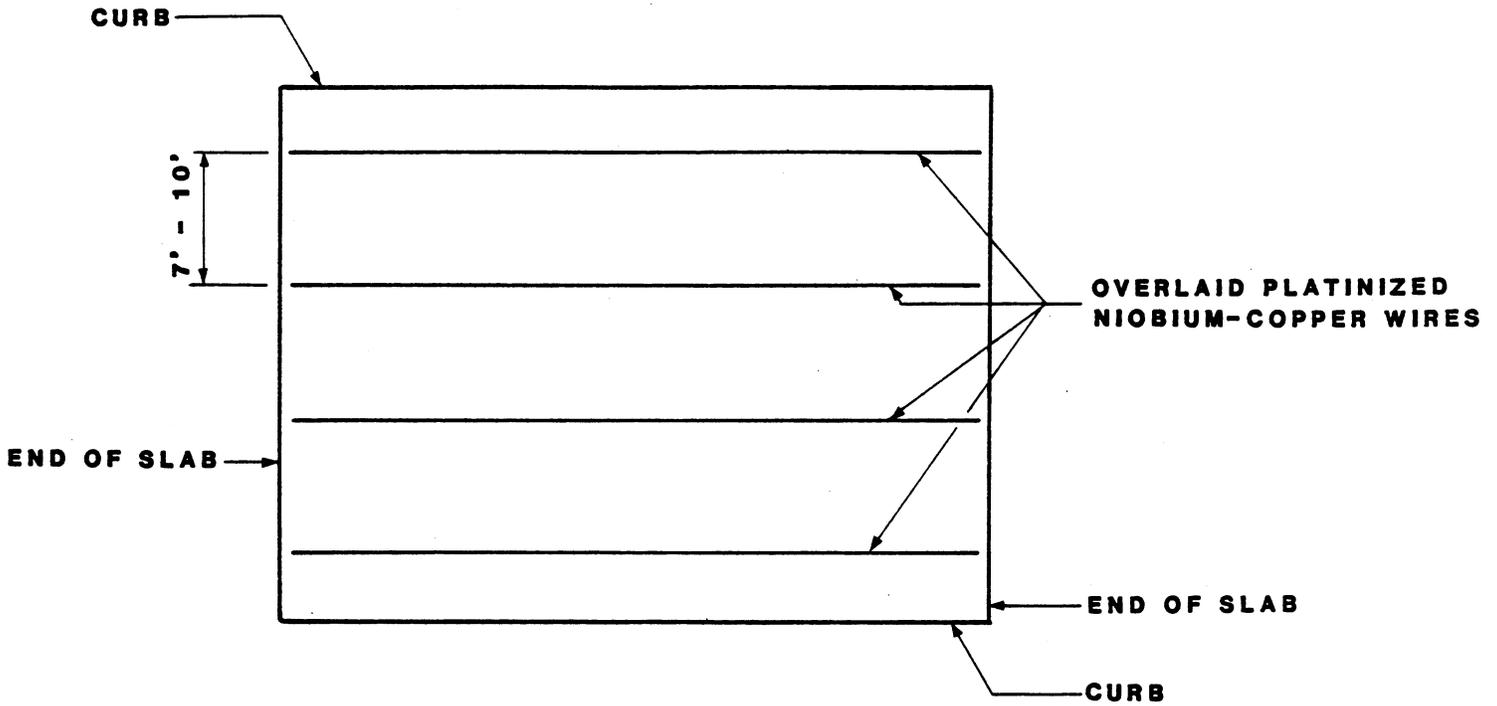


Figure 3. Conceptual plan showing top view of a CP system utilizing conductive portland cement concrete as an overlay and secondary anode.

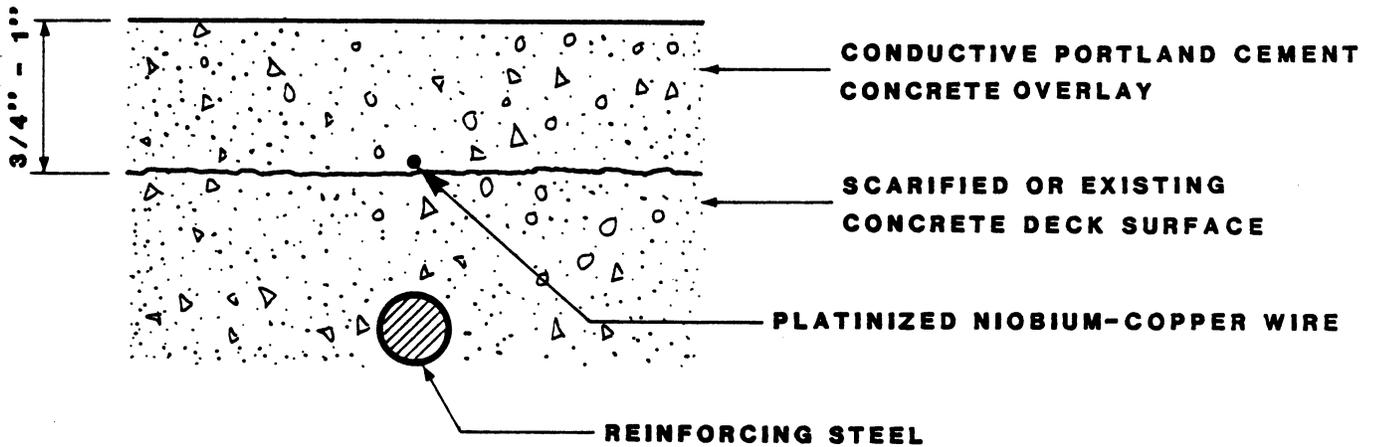


Figure 4. Conceptual plan showing portion of the transverse cross section of the CP system utilizing a conductive portland cement concrete.

BACKGROUND

The electrical resistivity of concrete has been reported to range between 600 and 4,500 ohm-cm.(1) The travel of electrical current through such a heterogeneous material can take three possible paths: (a) through the paste itself, (b) through the aggregate and cement paste in series, and (c) through the aggregate particles in contact with each other. Since the electrical resistivity of aggregate (about 10^4 to 10^9 ohm-cm) can be regarded as infinite in comparison to that of cement paste (about 1,000 to 1,500 ohm-cm), a high proportion of the electrical current is conducted through the cement paste. It is obvious, then, that the resistivity of a concrete is dependent upon the aggregate and the cement paste and that anything which reduces the resistivity of any of these components will affect the overall conductivity of the concrete.

Almost all reported efforts in the development of conductive concretes have been aimed at obtaining mixtures for use in applications such as grounding, eliminating static electricity, protecting against lightning, and screening out radio interference. Very little work has been aimed at developing mixtures for use in the cathodic protection of bridge substructures, and none at all for bridge decks.

One of the first known developments (perhaps in the 1940s) was the use of acetylene black to make portland cement mortars conductive. Such conductive mortars were used in the floors of hospital operating rooms, where static buildup might constitute a fire hazard because of the presence of flammable anesthetics.

In 1967, the use of conductive cement mortars as foundation materials for transmission towers was reported.(2) It was found that the most useful mixture employed a type II cement, a water-cement ratio (W/C) of 0.55 to 0.65, and a cement-coke ratio of 1.0 to 1.3. This mix exhibited resistivities of 100 ohm-cm after the initial cure and 2,350 ohm-cm after one year. It was also determined that improved conductance (232 ohm-cm after one year) could be obtained only by increasing the W/C to 0.9, which entailed a considerable sacrifice in the strength of the mortar.

In 1975, a conductive mortar for use as an overlay on reinforced bridge pilings, in conjunction with cathodic protection, was reported.(3) Coke was incorporated into a cement mortar made with type I cement. At cement-coke and water-cement ratios of 0.5, resistivities of approximately 30 ohm-cm were obtained.

In 1980, work with conductive concrete was reported by a communications company in England. Using a proprietary conductive, lightweight, carbonaceous aggregate at an aggregate-cement ratio of 2.0 and W/C of 0.58, the company produced a mix having a strength of 3,500 psi and resistivity of only 10-15 ohm-cm.(4)

It appears from these previous works that carbon black, coke, and carbonaceous aggregates may be efficacious additives in the formulation of a portland cement based concrete mixture suitable for use as a component of CP systems for bridge decks. This is not unexpected, since a common element in all these materials is carbon, which is a relatively good conductor. Based on an extension of this commonality, it was decided that carbon fibers should be given attention, since they possess very good conductivity and exceptional strengths. This was done in the present study.

EXPERIMENTAL PROCEDURE

Basically, the procedure used in the study consisted of the following steps:

- 1. Trial concrete mixes that incorporated various proportions of an additive, either by itself or in combination with another, were designed and prepared.

The additives examined included a coke, a carbon black, and carbon fibers. (An attempt to secure the conductive carbonaceous aggregate, which is probably also a coke, from England for experimentation was unsuccessful.) The coke had particle sizes ranging from approximately 0.8 to 13 mm, but was sieved to exclude particles larger than 6 mm. To eliminate any handling problem, the carbon black used was an aqueous dispersion. The carbon fiber used was a commercially available, high modulus fiber with a length of 0.25 in.

A type II cement and a coarse granite aggregate were used in almost all mixes.

- 2. Those mixes with reasonable workability were then cast into specimens in fabricated sample cells (Appendix A), so that the electrical resistivity of each mix could be monitored for at least 28 days during curing.
- 3. Those trial mixes that exhibited reasonably suitable conductivity or low resistivity were then replicated in large quantity so that enough specimens could be made for additional tests, according to ASTM Method C 192. These tests included measurements of the following characteristics:
 - (a) The compressive strength, as determined by ASTM Method 39, at 7 and 28 days.

- (b) The splitting tensile strength, as determined by ASTM Method C 496, at 7 and 28 days, to obtain an indication of the cohesion of the hardened mix.
- (c) The 28-day bond strength, as determined with a simple guillotine-like apparatus used to obtain comparative values of the shear bond strength for the conductive and conventional concrete mixes, as described in Appendix B.

Since a conductive concrete mix will be used like an overlay on existing concrete decks, it is necessary to have a measure of the ability of the mix to adhere to a hardened concrete base. There is currently no standard method available for measuring bond strengths.

- (d) The thermal stability, as determined by curing a set of duplicate bond-strength specimens of each mix for 28 days, subjecting them to 200 cycles of change in air temperature from 0°F to 100°F (at a rate of 3 cycles per day), and then applying a shear force at the bond interface.

In addition, the coefficient of thermal expansion of each test mix was determined by measuring the average change in length of each specimen when subjected to a change in temperature from 32.0°F to 120.0°F and vice versa. The length was measured according to ASTM Method C 490.

RESULTS

Prior to the actual experimentation with the electrically conductive additives, some tests were conducted to establish the effects of the conventional components of a concrete alone on resistivity. These tests involved the preparation of several conventional concrete mixes of various proportions of cement, water, and aggregate, and monitoring their resistivities through 28 days of curing. The observed effects of different weight ratios of cement-to-aggregate (C/A) and of W/C are illustrated in Figures 5 and 6, respectively.

Firstly, these results indicated that the hydration of cement was reflected in changes in the resistivity of the concrete with age in much the same manner that the strength of a concrete varies with age. This finding suggests that the water content has a major influence on the resistivity of a fresh concrete mix, and that as the free water reacts with the cement and becomes chemically bound, the resistivity increases until it becomes almost constant at around 28 days. Therefore, the resistivity at 28 days was used to facilitate comparisons.

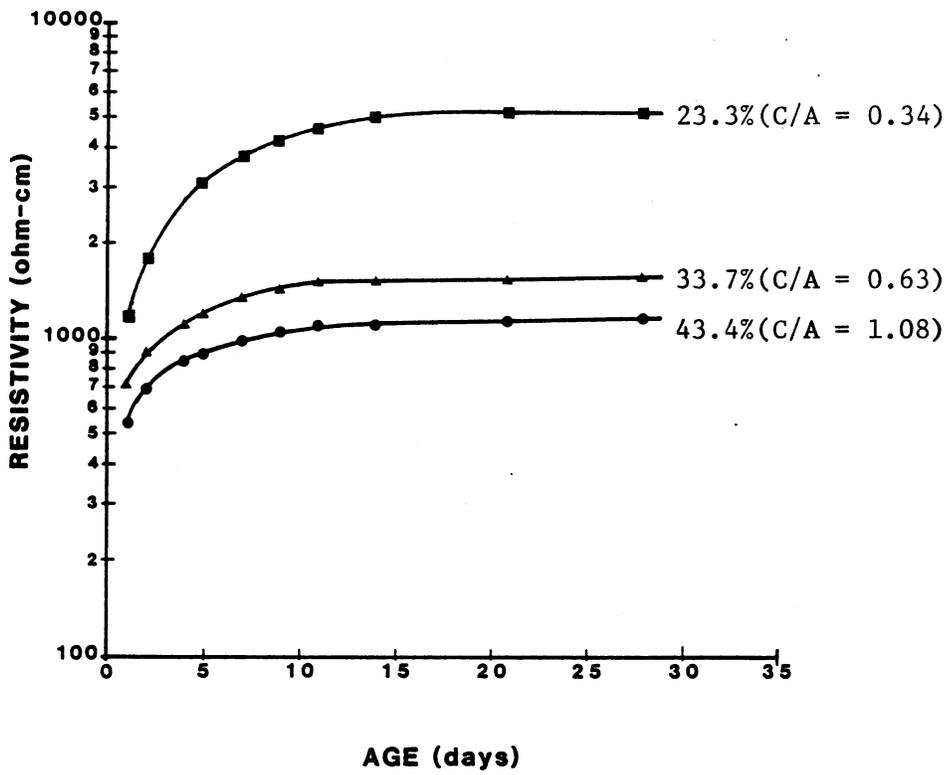


Figure 5. Electrical resistivity of concrete of different cement contents (% by weight) or cement-aggregate ratios. (The water-cement ratio was 0.38 for the three mixes.)

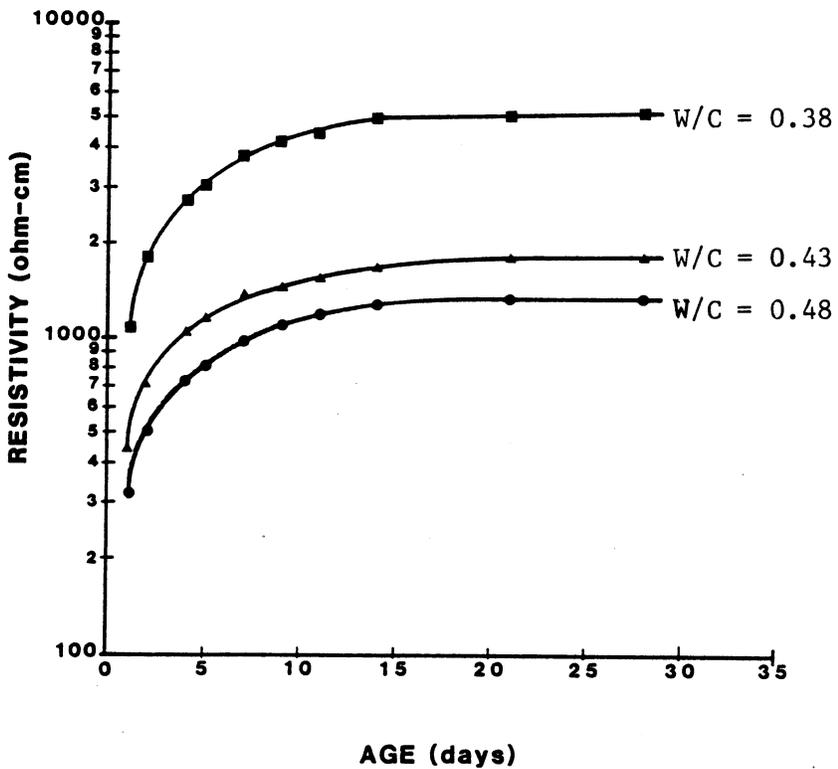


Figure 6. Electrical resistivity of concrete of different water-cement ratios. (The cement-aggregate ratio was 0.34 for all three mixes.)

More important, the results showed that the resistivity of a concrete can be reduced by increasing the C/A, while holding the W/C constant. As Figure 7 shows, however, there may be a limit in the C/A beyond which no significant reduction in resistivity is possible. Similarly, with the C/A held constant, the resistivity can be decreased by increasing the W/C, but only to a certain limit as illustrated in Figure 8.

Using these general relationships as guides, in addition to requiring reasonable workability, trial mixes incorporating various combinations of the additives were prepared. Table 1 gives a summary of the compositions and the resistivities of these trial mixes. When used as a substitute for conventional aggregate, or as a filler, coke appeared to provide a very significant reduction in resistivity, yielding values ranging between 20 and 122 ohm-cm. In addition, the 28-day compressive strength of one concrete was 5,230 psi. The addition of carbon fibers, as a second additive, provided a further reduction in resistivity, yielding values from 13 to 24 ohm-cm. However, the softness of the coke particles would make such concrete unsuitable for application on bridge decks. Therefore, further testing of the coke was not considered.

When carbon black alone was used as an additive, the resulting trial mixes had resistivities ranging from 623 to 2,890 ohm-cm, which represented, at best, a slight reduction from that for conventional concrete. These mixes exhibited extremely long setting times, some as long as 4 to 5 days. It appeared that the carbon black affected the normal setting characteristic of the concrete. The hardened concrete and mortar were also brittle, even to the touch, probably because the carbon particles attached to some cement particles to prevent their hydration and thereby adversely affect the cohesion of the cement paste. And similar to fly ash with a high carbon content, the carbon particles had an undesirable destabilizing effect on the air content of the fresh mixes.

In the initial trials, carbon fiber showed promise as an effective additive, as indicated by the relatively low resistivities shown in Table 1. In addition, the resulting hardened concrete and mortar were apparently lightweight and strong. For the trial mortar mixes, the observed resistivities ranged from 29 to 59 ohm-cm for carbon fiber contents of 1.6% to 1.9%. For the trial concrete mixes, the observed resistivities ranged from 51 to 509 ohm-cm for carbon fiber contents of 0.9% to 1.8%. However, the W/Cs were too high (i.e., 0.75 to 0.99). Assuming that an excessively high W/C also has such an adverse effect on the durability of a concrete containing carbon fibers as it has on conventional concrete, then an adjustment would be needed.

Subsequent trials involved mixes with increased carbon fiber contents and decreased W/Cs. The compositions and the corresponding physical properties of some of these mixes are given in Tables 2 and 3, respectively. During the trial mixing, it was noted that when the carbon fiber content was increased, more cement and water were needed to provide sufficient binding of the fibers and aggregate particles. This high demand

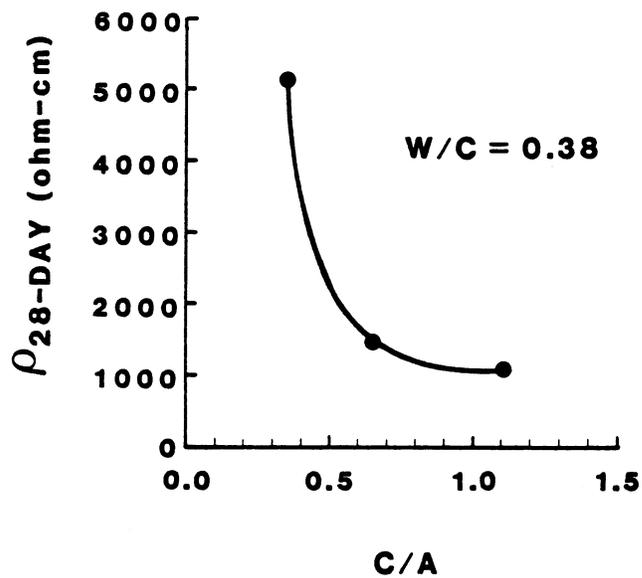


Figure 7. Effect of varying the C/A on the resistivity of concrete at 28 days.

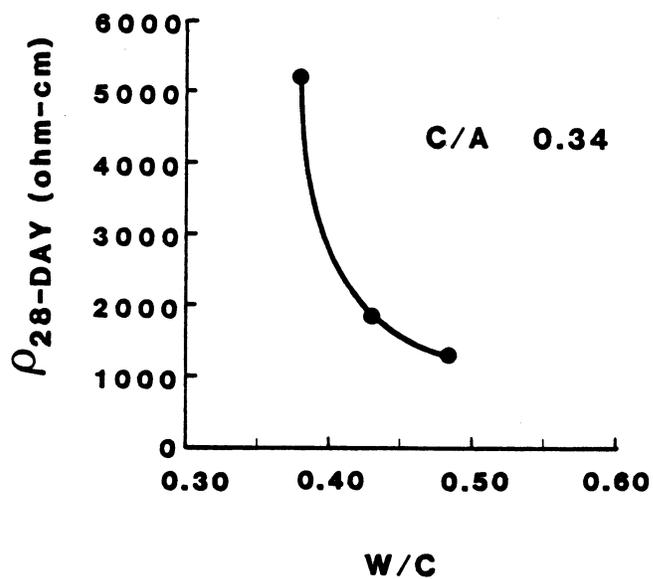


Figure 8. Effect of varying the W/C on the resistivity of concrete at 28 days.

TABLE 1

Compositions and Resistivities of Trial Mixes

Additive (%)*	Aggregates (%)		Cement (%)	W/C	Resistivity (ohm-cm)
	Coarse	Fine			
Coke (54.8-73.5)			17.3-30.2	0.50-0.53	20-122
Coke (46.4-50.7); carbon fiber (0.8-1.5)			32.3-33.7	0.50-0.54	13-25
Carbon black (0.7-2.1)		48.1-50.1	34.3-35.7	0.38-0.46	623-2,890
Carbon black (0.9)	23.9	32.2	29.1	0.48	1,520
Carbon fiber (0.9-1.8)	25.2-30.1	33.4-41.5	13.8-22.8	0.75-0.99	51-509
Carbon fiber (1.6-1.9)		41.0-48.6	34.6-41.0	0.40-0.43	29-59
Carbon fiber (1.6-2.3); carbon black (0.8-1.5)	12.4-13.4	8.9-17.9	40.3-51.7	0.47-0.62	5-23
Carbon fiber (1.8); carbon black (1.6)		47.2	33.6	0.46	17

* In percentage by weight.

for cement by the fibers is undoubtedly due to the relatively large surface area of the fibers. Consequently, the resulting mixes had relatively low densities (Table 2), which probably correlated better with the combined percentage of carbon fibers, cement, and water than with the percentage of fibers alone.

Since carbon fibers in the concrete provide additional paths for the conduction of electrical current, the resistivity of this type of concrete decreases with increased carbon fiber contents, as shown in Table 3. And similar to density, the resistivity for this type of concrete appeared to be slightly more dependent on the combined percentage of the carbon fibers, cement, and water than on the percentage of fibers alone, as illustrated in Figure 9. This dependency is not unexpected, since all three components facilitate the conduction of current in concrete. Among the three mixes, mix CF-3 appeared to have the lowest resistivity, at 72 ohm-cm. This resistivity represents an appreciable reduction of at least 90% from those of conventional concrete and may likely be suitable for use in cathodic protection systems for bridge decks. With Figure 9(b) as a guide, it is possible to achieve an even lower resistivity.

All three mixes possessed relatively good compressive and tensile strengths, as illustrated in Figures 10 and 11, respectively. Because of the interaction between the carbon fiber, cement, and water, it is difficult to define the effect of the carbon fiber alone on the compressive strength of a concrete; however, the carbon fibers appeared to have a slight, indirect beneficial effect. The beneficial effect on the tensile strength was more noticeable, and appeared to increase with increasing carbon fiber content.

In order for any of these carbon fiber concretes to perform satisfactorily as a bridge deck overlay, they must have good capacity to bond strongly to and be thermally compatible with a conventional concrete. Figure 12 shows that carbon fibers didn't exhibit any detrimental effect on the ability of these materials to bond to conventional concrete. On the contrary, the carbon fiber concretes exhibited a stronger bond to conventional concrete than the latter did to itself.

When these concretes were subjected to 200 cycles of change in the ambient air temperature from 0°F to 100°F, there appeared to be some loss in bond. As Figure 12 illustrated, the loss ranged from 6% to 29%, with mix CF-3 exhibiting the largest loss. However, it is believed that this relatively large loss for mix CF-3 likely resulted from its relatively low air content, which was only 3.2% (Table 2); and that with a higher air content of approximately 5.0%, the anticipated loss would likely be more in line with those of the other mixes. Nevertheless, even a bond strength of approximately 558 psi after 200 thermal cycles has to be considered favorable when compared to the measured bond strength of 559 psi between conventional concretes not subjected to thermal cycles.

TABLE 2

Compositions and Physical Characteristics of Some Concrete Mixes Containing Carbon Fibers

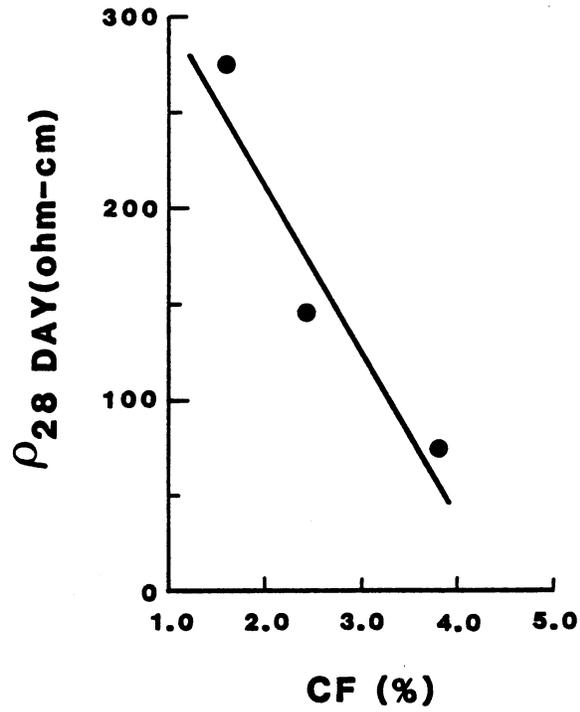
	Mix No.		
	CF-1	CF-2	CF-3
Coarse aggregate (%)*	26.7%	14.1%	11.0%
Sand (%)	35.9	19.1	14.8
Cement (%)	22.6	42.5	44.1
Water (%)	13.2	22.0	26.3
Carbon fiber (%)	1.6	2.4	3.8
W/C	0.59	0.52	0.60
CF + C + W (%)	37.4	66.8	74.2
C/CF	14.1	17.7	11.6
Slump (in)	1.4	2.3	2.4
Air Content (%)	5.0	4.8	3.2
Density (lb/ft ³)	136	118	115

*By weight.

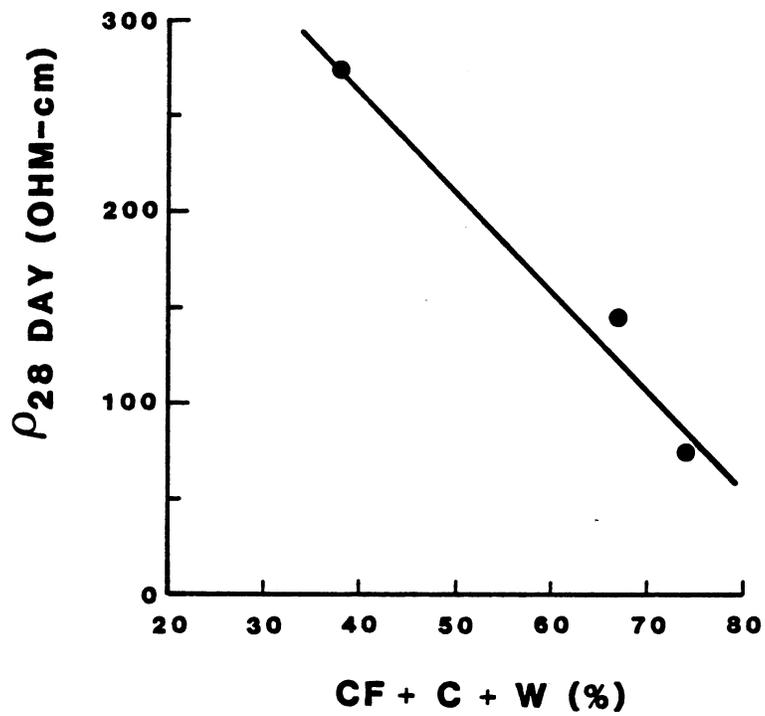
TABLE 3

Physical Properties of Some Concrete Mixes Containing Carbon Fibers

	Mix No.		
	CF-1	CF-2	CF-3
Resistivity (ohm-cm)	274	141	72
Compressive strength (psi) at			
7 days	4,020	4,180	4,130
28 days	5,640	6,130	5,910
Splitting tensile strength (psi) at			
7 days	517	544	655
28 days	691	758	784
Bond strength (psi) at 28 days and after 200 thermal cycles	718 672	823 732	786 558
Coefficient of thermal expansion (in/in-°F)	7.2×10^{-6}	7.7×10^{-6}	7.6×10^{-6}



(a)



(b)

Figure 9. Influence on resistivity: (a) carbon fiber alone, and (b) carbon fiber, cement, and water.

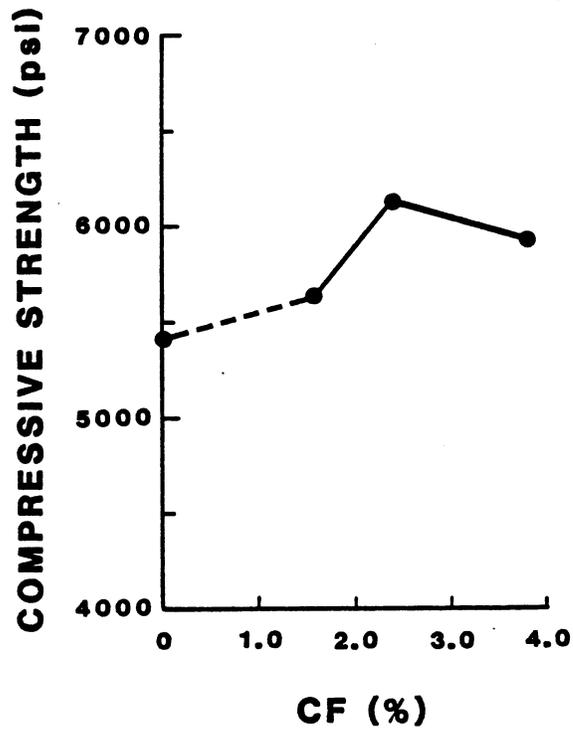


Figure 10. Effect of carbon fiber on compressive strength.

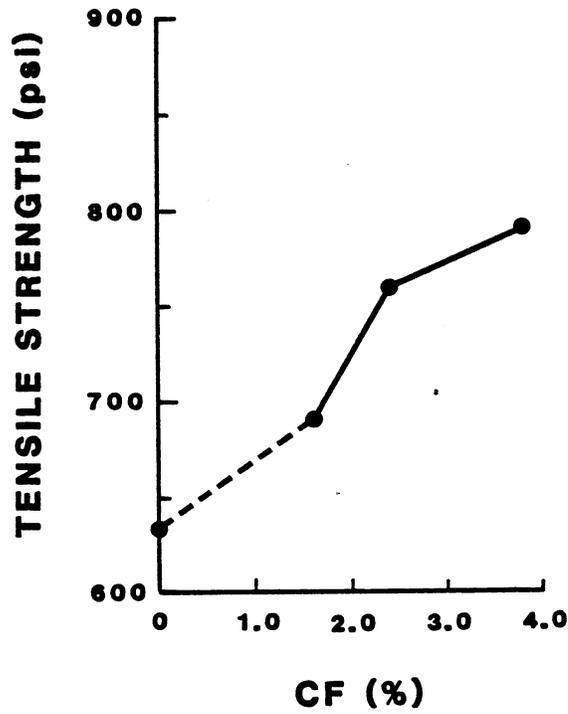


Figure 11. Effect of carbon fiber on tensile strength.

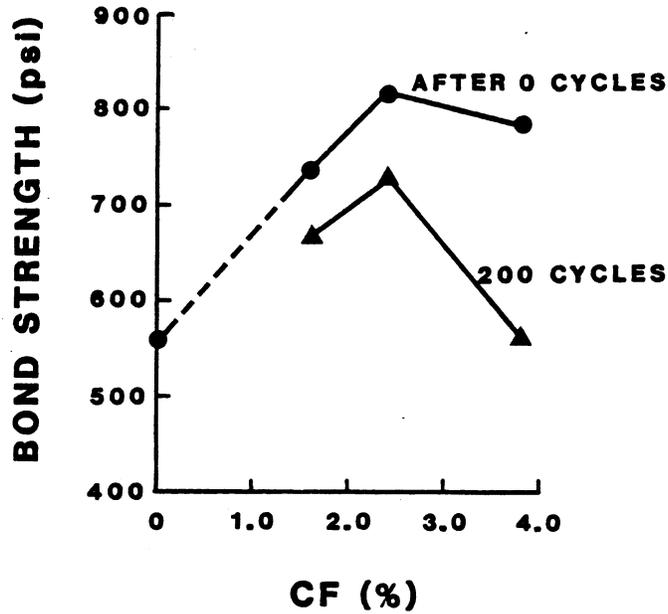


Figure 12. Effects of a carbon fiber content and number of thermal stress cycles on bond strength.

As shown also in Table 3, the measured coefficients of thermal expansion of these carbon fiber concretes ranged from 7.2×10^{-6} to 7.7×10^{-6} in/in-°F. These values are compatible with those reported for conventional concrete, which were from 3.6×10^{-6} to 6.8×10^{-6} in/in-°F. (5)

Table 4 shows the composition of a concrete mix (CFC-1) that contained carbon fibers and 0.6% of carbon black. This small amount of carbon black is believed to contribute to the further reduction in the resistivity to 54 ohm-cm, as indicated in Table 5. This mix possessed higher compressive and tensile strengths than those shown by the concrete that contained carbon fibers only, which most likely was attributable to its lower W/C. However, the carbon black appeared to have an adverse effect on the bond strength, which at 475 psi was lower than that of conventional concrete. The relatively large reduction in the bond strength after 200 thermal cycles is believed to have resulted from the slightly higher coefficient of thermal expansion and inadequate air content of the mix. When used with carbon fibers, carbon black didn't appear to have the destabilizing effect on air content that it had when used alone. It is possible to achieve an even lower resistivity by slightly increasing the W/C from 0.50 without adversely affecting the mechanical properties of the material to a significant extent.

384

TABLE 4

Composition and Physical Characteristics of a Concrete Mix Containing Carbon Fibers and Carbon Black

	Mix CFC-1
Coarse aggregate (%)*	10.0
Sand (%)	13.5
Cement (%)	48.3
Water (%)	24.1
Carbon fiber (%)	3.5
Carbon black (%)	0.6
W/C	0.50
CF + CB + C + W (%)	76.5
Slump (in)	0.9
Air content (%)	3.0
Density (lb/ft ³)	122

*By weight

TABLE 5

Physical Properties of a Concrete Mix Containing Carbon Fibers and Carbon Black

	Mix CFC-1
Resistivity (ohm-cm)	54
Compressive strength (psi) at	
7 days	4,930
28 days	6,090
Splitting tensile strength (psi) at	
7 days	791
28 days	937
Bond strength (psi) at 28 days and after 200 thermal cycles	475 169
Coefficient of thermal expansion (in/in-°F)	8.9×10^{-6}

CONCLUSION

In view of the preceding discussion, the following conclusions can be established.

1. The improvement of the conductivity of a portland cement concrete to a level that may be sufficient for the use of the concrete as a secondary anode in a cathodic protection system for reinforced concrete bridge decks would require the use of a suitable additive.
2. As an additive, carbon black appeared to provide only a slight improvement in the conductivity of concrete. In addition, it appeared to create difficulty in achieving a desirable air content in the concrete mix, and to weaken the concrete.
3. As demonstrated by the properties of mix CF-3, carbon fibers appeared to provide sufficient conductivity without any concomitant adverse effect on the mechanical properties of the concrete.
4. Further improvement in conductivity may be achieved by supplementing the carbon fibers with a small amount of carbon black. However, there was uncertainty on whether it was the presence of the carbon black or the low air content of the mix that resulted in the large loss in the bond strength of the concrete after 200 thermal cycles.
5. Electrically conductive concrete has potential for use as a secondary anode in the cathodic protection of bridge decks. Such concrete warrants further study, which should include testing its effectiveness and durability, under different current levels, when applied as an overlay on reinforced concrete slabs treated with deicing chemicals.

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APPENDIX A

MEASUREMENT OF ELECTRICAL RESISTIVITY

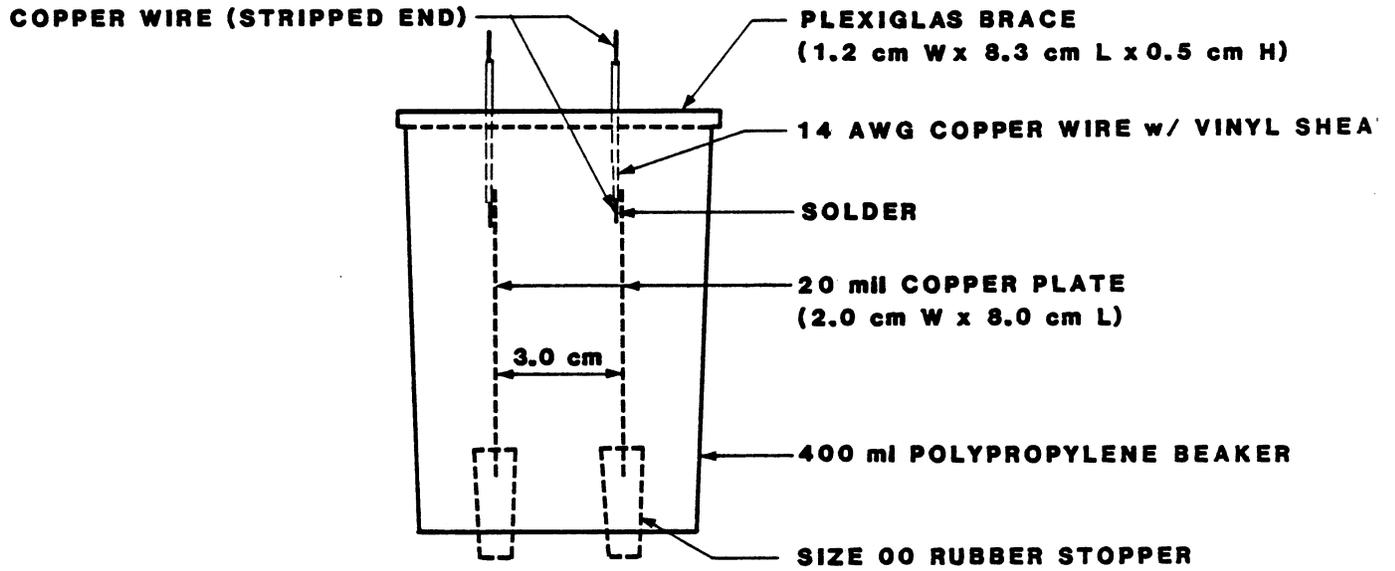
Figure A-1 shows a sample cell fabricated to facilitate the measurement of comparative electrical resistances of concrete mixes. The concrete mix is poured into the disposable sample cell in three layers. The cell is externally vibrated after each layer is poured. After the cell is completely filled, i.e., to the base of the plexiglas brace, the mouth of the cell is covered with two layers of flexible laboratory film to prevent excessive evaporation.

The resistance of the concrete mix is measured across the top of the two copper wires with a multimeter. Then, the resistivity of the material is calculated from the relationship

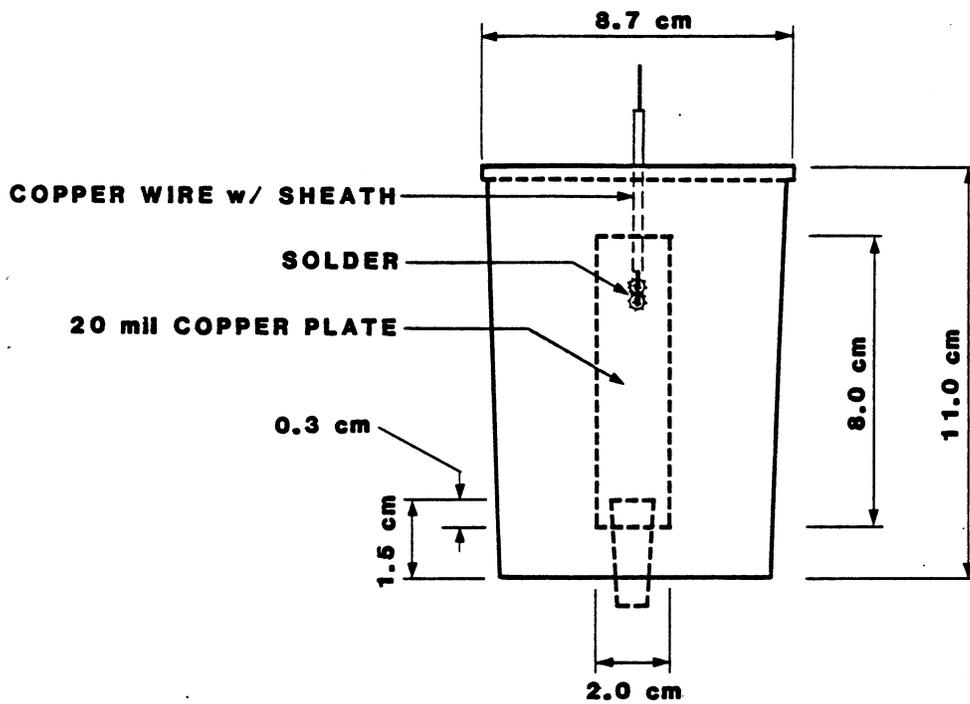
$$p = RC,$$

where

- p = the resistivity, in ohm-cm,
- R = the resistance, in ohm, and
- C = the resistivity constant of the cell, i.e. 10.9 cm.



FRONT VIEW



SIDE VIEW

Figure A-1. Sample cell for measurement of the electrical resistance of concrete.

APPENDIX B

MEASUREMENT OF COMPARATIVE BOND STRENGTH

The comparative ability of a mix to adhere to a concrete base, or its bond strength, was measured using the guillotine-like apparatus shown in Figure B-1 and described elsewhere. (6) The concrete bases used were obtained by sawing, in halves, 4-in-by-8-in concrete cylinders that were prepared and cured for 28 days according to ASTM Method C 192. Each half was placed in a plastic mold for 4-in-by-8-in cylinders, with the sawed surface facing upward. Then, in preparing a specimen for the measurement of its bond strength, a portion of each test mix was cast over the exposed sawed surface of the concrete base to form a 3-in layer and allowed to cure for 28 days in a manner similar to the procedure described in ASTM C 192. Duplicate specimens were made for each measurement.

A shear load was applied parallel to the bonded interface of the specimen through a spherical bearing block of the apparatus at a rate of 2,000 lb/in²/min. The shear bond strength, S, was then calculated from

$$S = L/A,$$

where

- L = the maximum load carried by the specimen, and
- A = the bond, or cross sectional, area of specimens.

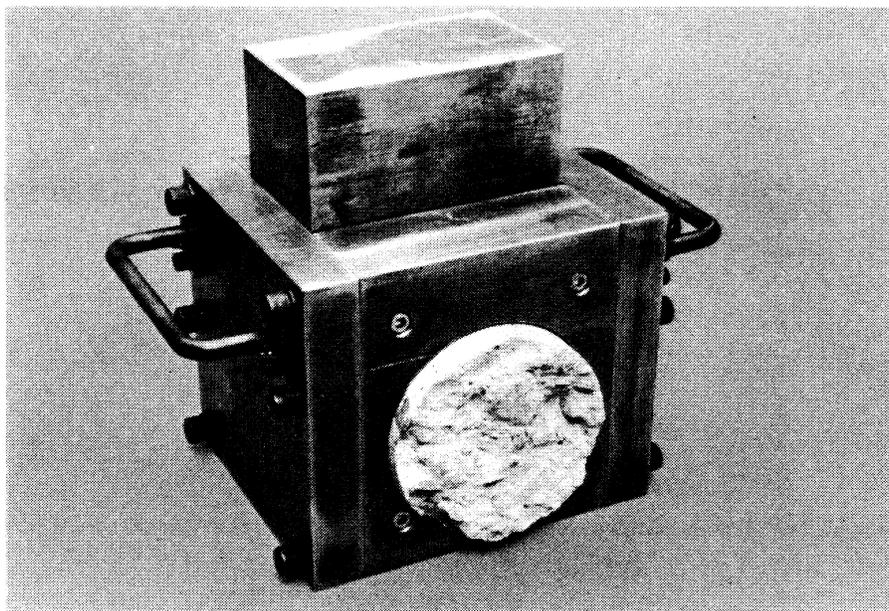
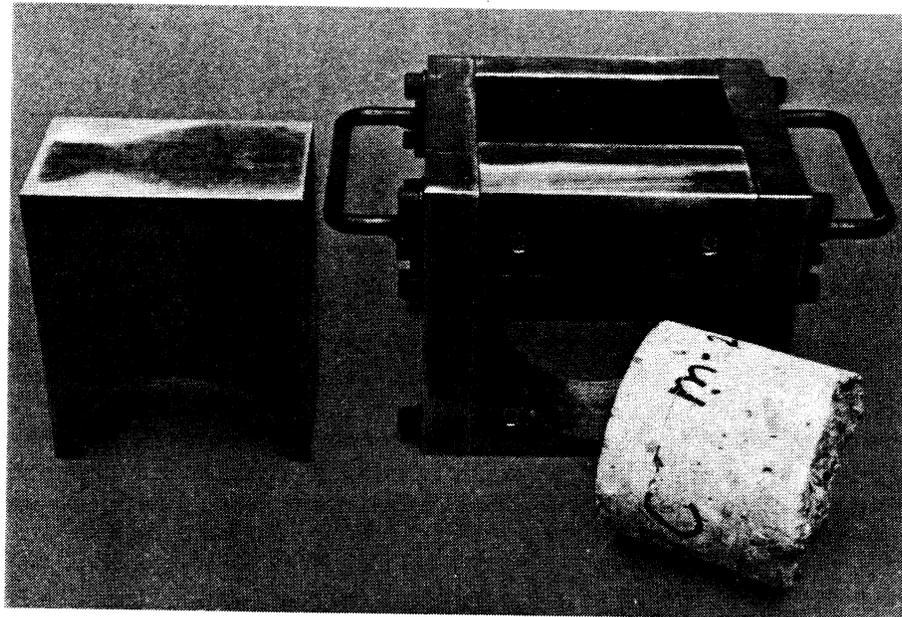


Figure B-1. Apparatus used to measure the comparative shear bond strength of a mix.