Effects of Rigid Overlays on Corrosion Currents of Reinforcing Steel in Bridge Decks

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Corrosion currents of reinforcing steel in bridge decks scheduled for rehabilitation with rigid concrete overlay systems were measured using a three-electrode linear polarization (3LP) device. Ten bridge decks in Ohio were included in the study. Overlays were then placed using latex-modified concrete (LMC), superplasticized "dense" concrete (SDC), and condensed silica fume concrete (CSFC). Corrosion currents were then remeasured 1 and 2 years after initial placement of the overlays. Results of the study indicate that corrosion currents can be measured in bare and overlaid concrete bridge decks using the commercially available 3LP instrumentation. The equipment is rugged, practical for field use, and capable of yielding reproducible results. The installation of rigid concrete overlays appears to have an effect on corrosion current in the steel present in the substrate deck. In the period covered by the present study (2 years after installation), corrosion currents appeared to decrease with time for most of the LMC and CSFC overlays. Results for SDC overlays were not as clear, a mix of increases and decreases being noted. Most consistent decreases in corrosion current throughout the study occurred for the CSFC overlays. This may be due to their generally lower permeability as opposed to LMC or SDC systems.

Of the many solutions proposed to the problem of bridge deck deterioration, rigid overlays have certain advantages, including familiarity of technology, restoration of riding quality, and relatively low cost. Latex-modified concrete (LMC) overlays are the most widely used system in Ohio and they have exhibited generally good performance, at least in terms of their ability to reduce chloride penetration. Mix designs used for LMC overlays usually call for 298 kg (658 lb) of cement, relatively low water content [water-cement ratio (w/c) = 0.39 or less] and 15 percent (by cement weight) of a 46 percent emulsion of styrene-butadiene latex. In a recent study by Whiting and Dziedzic, spalling of LMC overlays was detected, especially on structures on which LMC had been in service for more than 10 years (*1*). The distress may have been due, at least in part, to ongoing corrosion in the substrate concrete deck. Similar distress in LMC overlays in Ohio was studied by Abdulshafi et al., who attributed problems to ongoing corrosion in the original deck and deficiencies in construction practices (*2*).

Superplasticized "dense" concrete (SDC) incorporates a cement content of approximately 372 kg (820 lb), a maximum w/c of 0.36, with superplasticizers being used to obtain a workable concrete. Whiting and Kuhlmann (*3*) indicate significantly higher permeabilities for SDC than for LMC, as do Whiting and Dziedzic (*1*). As SDC overlays in Ohio have been in service for only a few years, distress similar to that observed on the oldest LMC overlays has not yet been observed.

Condensed silica fume concrete (CSFC) overlays use a relatively high cement content of 270 to 320 kg (600 to 700 lb), low w/c (in many cases less than 0.30), and sufficient high-range water reducer to obtain a workable concrete mixture. Laboratory data indicate that reduction in permeability to chloride ions is a function of silica fume addition, the greatest reductions occurring at additions above 10 percent by weight of cement (*4*). Short-term field data (*1,5*) are promising, but long-term field performance data are lacking.

FHWA laboratory studies indicate a continuance of corrosion beneath rigid overlays placed on base slabs where corrosion had begun before placement of the overlay (*6*). These laboratory studies have produced some concern about the long-term viability of rigid overlays placed on actively corroding decks. If corrosion is indeed proceeding at a significant rate beneath these overlays, their ultimate service life may be impaired and their cost-effectiveness greatly reduced. There is a need for data on corrosion rates of reinforcing steel in bridge decks rehabilitated using rigid overlays, so that better data on the life-cycle cost of these systems may be developed.

RESEARCH APPROACH

Basis for Measurement Technique

Corrosion rates were measured using a linear polarization technique. The three-electrode linear polarization (3LP) technique was validated as a means of estimating rate of corrosion of steel in concrete in laboratory work performed at the U.S. National Bureau of Standards (*7*). The technique is based on the assumption that small changes in the potential of a freely corroding electrode (i.e., an electrode at a potential close to the corrosion potential) have a linear relationship with current. The amount of current change is proportional to the corrosion current (and in turn the corrosion rate), according to the equation

$$i_{corr} = K \frac{\Delta i_{app}}{\Delta E} \quad (1)$$

Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, Ill. 60077.

where

ΔE = voltage change required to obtain Δi_{app},
Δi_{app} = current density change resulting from voltage change ΔE (mA/m^2),
K = proportionality constant, and
i_{corr} = corrosion current density for the electrode (mA/m^2).

The proportionality constant is a function of the anodic and cathodic "Tafel slopes" (i.e., the relationship between current and voltage levels outside the linear region) and is dependent on the particular system being polarized. Clear suggests the use of an anodic Tafel slope of 150mV/decade and a cathodic Tafel slope of 250 mV/decade (*8*). If one assumes uniform corrosion and a constant rate over time, i_{corr} for steel can be converted to millimeters per year by multiplying i_{corr} by 0.00115. Such calculations are valid if monitoring with time is performed at close intervals or an assumption is made that the corrosion rate has been constant in the past or will be in the future. It was thought more appropriate for the purposes of the present study to express the results simply in terms of corrosion current, in milliamperes per square meter of reinforcing steel, as only yearly monitoring was planned for purposes of assessing relative corrosion rates.

Instrumentation

A commercially available version of the 3LP equipment has been recently developed and marketed. To make the measurement, a ground lead is first attached to reinforcing steel known to be continuous with the bar under test. The portable probe is then placed directly over the steel to be tested. The effective length of steel tested is 178 mm (7 in.). The portable probe serves as the counter electrode and consists of a copper mesh screen that makes contact with the concrete surface through a sponge dampened with a solution of wetting agent. Care must be taken not to oversaturate the sponge because doing so would place the effective area of the test outside of the probe location. The reference electrode is a miniature copper-sulfate electrode (CSE) that passes through a plastic pipe in the center of the probe body.

The test is carried out by first ensuring that the potential measured by the reference electrode is stable. A null balance circuit is then used to offset the potential to a value of 0.0 mV. The operator then slowly increases the test current using the potentiometer until the potential meter registers 4 mV. At this point the current (in milliamperes) is recorded. The process is repeated at 4 mV intervals up to a value of 12 mV. At this point the current in reduced to zero and the potential allowed to decay to its starting value. A second run is then performed to verify the first. The data are checked for linearity by plotting potential versus current and examining the relationship. In most cases, linear regression coefficients of .98 or above are recorded, indicating excellent linearity. Software applied with the device is used to calculate corrosion current and corrosion rate. Results for the two runs are then averaged.

Sampling Plan

The test program was designed so that all three rigid overlay systems (i.e., LMC, SDC, and CSFC) would be included in the evaluations. During the first year of testing it was necessary to locate jobs where the deck surface had been prepared but where the overlay had not yet been placed. It was important to ensure that all deck preparation work had been completed, otherwise the concrete surrounding the test area might be removed and one would be measuring the corrosion current of the rebar embedded in new overlay concrete rather than in the original deck. Ten decks were finally selected. Deck numbers for this study, ODOT bridge numbers, locations, and year of initial construction are given in Table 1. The suite of overlays included four LMC, three SDC, and three CSFC overlays, all of which were placed in summer 1989.

CSE readings were obtained on selected areas of the deck that had not been disrupted by overlay preparation procedures. Because in many cases, overlay preparation involved removing major portions of the concrete cover, the potential measurements were carried out simply to establish candidate locations for the 3LP measurements and not to obtain overall information relating to potentials across the deck, as would be done in potential "mapping" of an intact deck surface. From the measured potentials, 3LP test locations were chosen to cover a range of potentials. As seen in Table 1, 46 test locations were included in the study.

TABLE 1 Identification of Field Test Locations

Deck	Overlay Type	Location	Year of Deck Construction	Number of Test Locations
1	SDC	Smith Road over I-71	1964	2
2	LMC	Rt 674 Sbl. over Turkey Run	1955	3
3	SDC	S.R. 79 Nbl. over I-70	1958	6
4	LMC	Rt. 18 Wbl. over Rt. 20	1968	4
5	SDC	Rt. 797 Nbl. over I-70	1963	6
6	CSFC	Rt. 66 over Tiffin River	1958	3
7	CSFC	Rt. 35 Wbl. over Scioto River	1969	8
8	LMC	Rt. 27 Sbl. over Miami River	1970	4
9	CSFC	RT. 541 Nbl. over Birds Run	1962	4
10	LMC	I-70 Ebl. over Penn-Central	1969	6

FINDINGS

Year 1 Results

Corrosion currents measured during the first year of testing, along with measured CSE potentials at each test location, are presented in Table 2. ASTM C876-91 suggests the following (nonmandatory) interpretation of CSE potentials taken on aboveground reinforced concrete structures:

1. If potentials over an area are more positive than −0.20 V CSE, there is a greater than 90 percent probability that no reinforcing steel corrosion is occurring in that area at the time of measurement.
2. If potentials over an area are in the range of −0.20 to −0.35 V CSE, corrosion activity of the reinforcing steel in that area is uncertain.
3. If potentials over an area are more negative than −0.35 V CSE, there is a greater than 90 percent probability that

TABLE 2 Potentials and Corrosion Currents in Year 1 Tests

Deck No.	Overlay Type	Test Location	CSE Potential (neg. mV)	Corrosion Current (mA/sq.m.)
1	SDC	1	169	20.2
		2	120	14.4
2	LMC	1	282	19.1
		2	315	24.1
		3	135	18.4
3	SDC	1	392	69.6
		2	365	75.8
		3	122	41.2
		4	340	35.6
		5	154	43.1
		6	463	83.2
4	LMC	1	260	39.8
		2	319	51.3
		3	169	14.7
		4	293	23.0
5	SDC	1	83	49.9
		2	281	47.5
		3	209	42.9
		4	135	21.4
		5	232	23.9
		6	183	12.2
6	CSFC	1	408	60.4
		2	220	13.0
		3	137	14.1
7	CSFC	1	215	16.5
		2	135	19.1
		3	231	46.6
		4	162	12.4
		5	76	19.3
		6	176	24.5
		7	278	62.1
		8	237	41.8
8	LMC	1	157	13.2
		2	238	20.3
		3	253	28.2
		4	266	41.2
9	CSFC	1	342	35.6
		2	250	8.4
		3	204	8.5
		4	161	6.6
10	LMC	1	200	11.7
		2	246	18.6
		3	244	12.1
		4	98	7.6
		5	171	12.6
		6	266	14.3

1 ma/sq.m. = 0.0929 ma/sq.ft.

reinforcing steel corrosion is occurring in that area at the time of measurement.

It should be noted that these guidelines are not strictly applicable in the current study, because the locations shown in Table 2 are spot measurements and do not represent an average of potentials over a wide area of the deck. The guidelines were used to select the locations shown in Table 2, hence the range of potentials for each deck studied. In each case, an attempt was made to select spots of high, moderate, and low potential to include in the set of measurements for each deck. In most cases, however, it was difficult to locate areas of potentials more negative than −350 mV CSE; therefore, very few of the test locations in this study fell into Category 3 of the ASTM guidelines as presented earlier.

Clear (*8*) has suggested the following interpretation of corrosion current data generated using the 3LP technique:

1. Corrosion current less than 2 mA/m^2 (0.20 mA/ft^2): no corrosion damage expected.
2. Corrosion current between 2 and 10 mA/m^2 (0.20 and 1.0 mA/ft^2): corrosion damage possible in 10 to 15 years.
3. Corrosion current between 10 and 100 mA/m^2 (1.0 and 10 mA/ft^2): corrosion damage expected in 2 to 10 years.
4. Corrosion current in excess of 100 mA/m^2 (10 mA/ft^2): corrosion damage expected in 2 years or less.

Of the 46 3LP measurements taken, none falls into Category 1 of Clear's suggested interpretation, four fall into Category 2, and the rest fall into Category 3. None of the corrected corrosion currents exceeded 100 mA/m^2 (10 mA/ft^2). The purpose of the present study was relative in nature and not designed to develop predictions of service life as given in Clear's guidelines, but one could also view the four categories as representing a range of corrosion intensities, varying from little or no corrosion activity (Category 1), low activity (Category 2), moderate activity (Category 3), and high activity (high end of Category 3 or Category 4). Viewed in this manner, the vast majority of measurements represent moderate or moderately high corrosion activity. On the average, corrosion activity is highest on Deck 3 and lowest on Deck 10. The rest of the decks include a range of corrosion currents, depending on the location chosen.

The relationship between measured corrosion currents and CSE potentials at the same locations is shown in Figure 1. There is only a very general trend to the data, and in many instances corrosion currents in the middle of the "moderate" range are associated with either very low or relatively high CSE potentials. Even the lowest corrosion currents are associated with potentials ranging from well into the passive range (more positive than −100mV CSE) to well into the region of uncertainty. It is easy to see, therefore, that potentials in themselves can be a misleading indicator of corrosion activity and that selected application of the 3LP or other techniques designed to measure actual corrosion currents may be a valuable adjunct to traditional potential surveys of bridge decks.

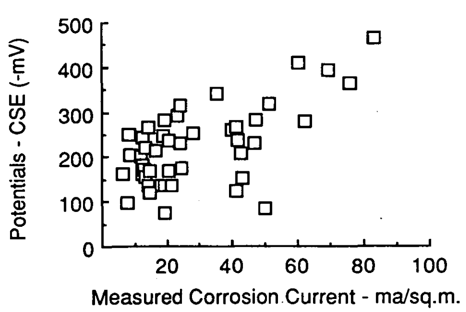

FIGURE 1 Comparisons of measured corrosion currents and CSE potentials.

Year 2 Results

The 10 test sites were revisited during summer 1990, approximately 12 months after the initial data were collected. In comparison with Year 1, temperatures were, for the most part, somewhat lower overall, reflecting the cool, wet summer of 1990 in Ohio. Results of 3LP testing are presented in Table 3; also presented are the changes that occurred in corrosion currents between the two sets of readings. Substantial differences can be seen in many instances, but a clear trend is difficult to ascertain. The most consistent results appear to be obtained in the case of the CSFC overlays (Decks 6, 7, and 9). Almost all readings show a decrease between Years 1 and 2, and in several cases the decrease is substantial. For instance, Locations 3 and 7 on Deck 7 exhibited fairly high corrosion currents of 46.6 to 62.1 mA/m^2 (4.3 to 5.7 mA/ft^2) in Year 1, yet by Year 2 they had decreased to 15 to 20 mA/m^2 (1.4 to 1.8 mA/ft^2). LMC overlays also exhibited some decreases in corrosion current, for instance on Decks 4 and 8. A Verglimit asphaltic concrete overlay had been placed on top of the LMC overlay on Deck 8 to reduce icing conditions during winter. Hence, there is some question as to the reliability of the data obtained from this site. At other LMC sites corrosion currents stayed essentially the same or exhibited relatively small increases. At Deck 2 a fairly substantial increase was noted at Location 1. However, readings in general on this deck were somewhat unstable, and it was difficult to obtain reliable readings even after the reinforcing steel was exposed by coring so as to make an unambiguous connection to the rebar mat. SDC sites show both increases and decreases in corrosion rates, and as noted no clear trends are evident.

Year 3 Results

The 10 test sites were revisited for the final time in summer 1991, approximately 24 months after the initial data were obtained. Though not quantified in the data sets, the summer of 1991 was much drier over most of Ohio than that of 1990, which would tend to contribute to lower corrosion rates, all other factors being equal. In addition to corrosion rate data at Deck 8, where the extremely low readings obtained through the asphaltic overlay were questioned, circuit resistance between the mesh counterelectrode and the reinforcing steel were determined using a portable A.C. ohmmeter (Nilsson Model 400 soil resistance meter). The stated maximum circuit resistance through which the 3LP instrument can reliably read

TABLE 3 Corrosion Currents in Year 2 Tests

Deck No.	Overlay Type	Test Location	Corrosion Current (mA/sq.m.)	Change from Year 1 (mA/sq.m.)
1	SDC	1	34.9	14.6
		2	27.4	13.0
2	LMC	1	41.3	22.3
		2	23.3	- 0.9
		3	u.r.	u.r.
3	SDC	1	106.0	36.4
		2	38.9	-36.9
		3	41.7	0.4
		4	21.4	-14.2
		5	16.1	-26.9
		6	40.4	-42.8
4	LMC	1	21.1	-18.7
		2	32.2	-19.2
		3	21.3	6.6
		4	22.0	- 1.1
5	SDC	1	81.7	31.8
		2	67.0	19.5
		3	113.7	70.7
		4	76.3	54.9
		5	62.6	38.8
		6	52.1	39.9
6	CSFC	1	31.9	-28.5
		2	26.4	13.3
		3	14.7	0.6
7	CSFC	1	5.9	-10.5
		2	10.1	-8.9
		3	15.0	-31.6
		4	11.4	- 1.0
		5	15.7	- 3.6
		6	16.3	- 8.3
		7	20.1	-42.0
		8	34.3	- 7.4
8	LMC	1	1.6	-11.63
		2	0.0	-20.34
		3	2.5	-25.73
		4	0.6	-40.58
9	CSFC	1	11.8	-23.79
		2	8.2	- 0.22
		3	7.1	- 1.40
		4	6.9	0.32
10	LMC	1	15.5	3.77
		2	35.3	16.68
		3	16.9	4.84
		4	8.6	0.97
		5	10.4	- 2.15
		6	12.3	- 2.05

u.r. Readings unstable at this location
1 ma/sq.m. = 0.0929 ma/sq/ft.

is 15,000 ohms. Readings obtained at Deck 8 land considerably above these values, indicating the data to be undependable.

Corrosion currents are shown in Table 4. Also presented are the changes as compared with the initial series of measurements. In contrast to the Year 2 results, almost all readings obtained during Year 3 exhibit lower values of corrosion current than were present before the overlays were placed. If the data for Deck 8 are disregarded because of the high circuit resistances noted earlier, then all of the LMC and CSFC sites exhibited lower corrosion currents than before overlay placement. Data for SDC, as in Year 2, are still variable in either direction—that is, some locations exhibit lower corrosion currents than the initial condition, some exhibit higher.

A summary of the difference between corrosion currents at Years 2 and 3 and Year 1 is shown in Figure 2. The chart indicates that in many cases, the presence of rigid overlays after 2 years of service appears to have resulted in some lessening of corrosion current at the reinforcing steel. Most of these decreases range between 10 and 20 mA/m^2 (1 and 2

TABLE 4 Corrosion Currents in Year 3 Tests

Deck No.	Overlay Type	Test Location	Corrosion Current (mA/sq.m.)	Change from Year 1 (mA/sq.m.)
1	SDC	1	18.1	- 2.2
		2	16.6	2.2
2	LMC	1	7.8	-11.3
		2	8.3	-15.8
		3	5.0	-13.5
3	SDC	1	16.5	-53.2
		2	9.0	-66.7
		3	12.6	-28.6
		4	13.7	-22.0
		5	6.1	-36.9
		6	30.7	-52.5
4	LMC	1	6.8	-33.0
		2	10.8	-40.6
		3	12.5	- 2.3
		4	17.7	- 5.4
5	SDC	1	39.5	-10.4
		2	42.9	- 4.5
		3	62.5	19.6
		4	56.5	35.1
		5	47.3	23.4
		6	47.5	35.3
6	CSFC	1	11.1	-49.3
		2	11.0	- 2.0
		3	6.4	- 7.8
7	CSFC	1	9.0	- 7.4
		2	8.5	-10.5
		3	11.3	-35.3
		4	6.6	- 5.8
		5	8.7	-10.5
		6	6.6	-18.0
		7	10.5	-51.6
		8	13.9	-27.9
8	LMC	1	18.1	4.8
		2	0.4	-19.9
		3	15.8	-12.4
		4	10.5	-30.7
9	CSFC	1	10.3	-25.3
		2	4.4	- 4.0
		3	3.0	- 5.5
		4	3.7	- 2.9
10	LMC	1	9.9	- 1.8
		2	12.5	- 6.1
		3	11.4	- 0.6
		4	0.9	- 6.8
		5	1.1	-11.5
		6	12.3	- 2.0

1 ma/sq.m. = 0.0929 ma/sq.ft.

mA/ft^2). Reexamination of Table 4 indicates that these decreases have placed most corrosion currents for LMC and CSFC overlays in the vicinity of 10 mA/m^2 (1 mA/ft^2) or less. This would be in or near Category 2 as previously defined. Considering that most of the readings initially fell within Category 3, an interpretation using Clear's system would be that corrosion activity has been reduced from that which would be expected to cause damage in 2 to 10 years to that which would be expected to cause damage in 10 to 15 years. If these interpretations are correct, the latter range could be taken as representing the expected lifetime of the overlays.

CONCLUSIONS

From the results of the study described in this paper, the following conclusions may be drawn:

- Corrosion currents can be measured in bare and overlaid concrete bridge decks using the commercially available 3LP instrumentation. The equipment is rugged, practical for field use, and capable of yielding reproducible results.
- The installation of rigid concrete overlays does have an effect on corrosion current in the steel present in the substrate

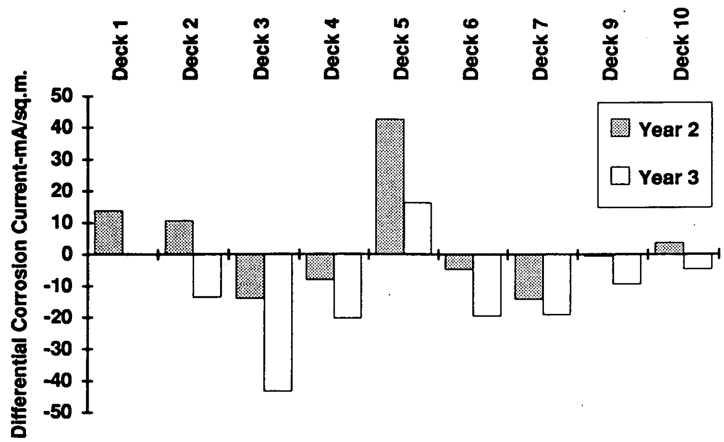

FIGURE 2 Corrosion currents relative to Year 1 values for decks surveyed.

deck. In the period covered by the present study (2 years after installation), corrosion currents appeared to decrease with time for most of the LMC and CSFC overlays. Results for SDC overlays were not so clear.

• Most consistent decreases in corrosion current throughout the period of the study occurred for the CSFC overlays. This may be due to their generally lower permeability as opposed to LMC or SDC systems.

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REFERENCES

1. D. Whiting and W. Dziedzic. Chloride Permeabilities of Rigid Concrete Bridge Deck Overlays. In *Transportation Research Record 1234*, TRB, National Research Council, Washington, D.C., 1989, pp. 24–29.
2. O. Abdulshafi, B. Kvammen, and K. Kaloush. *Premature Failure of Latex Modified Concrete Bridge Decks Overlaid in Ohio*. Report FWHA/OH-90/013. Ohio Department of Transportation, Columbus, 1990.
3. D. Whiting and L. Kuhlmann. Curing and Chloride Permeability. *Concrete International—Design and Construction*, Vol. 9, No. 4, April 1987, pp. 18–21.
4. S. L. Marusin. Chloride Ion Penetration in Conventional Concrete and Concrete Containing Condensed Silica Fume. In *ACI SP-91: Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, Vol. 2, American Concrete Institute, Detroit, Mich., 1986, pp. 1119–1133.
5. D. Bunke. ODOT Experience with Silica Fume Concrete. In *Transportation Research Record 1204*, TRB, National Research Council, Washington, D.C., 1988, pp. 27–35.
6. R. E. Hay and Y. P. Virmani. North American Experience in Concrete Bridge Deterioration and Maintenance. *Proc., Symposium on Concrete Bridges—Investigation, Maintenance, and Repair*, Kensington, London, England, Sept. 1985.
7. E. Escalante, E. Whitenton, and F. Qiu. *Measuring the Rate of Corrosion of Reinforcing Steel in Concrete—Final Report*. Report NBSIR 86-3456. National Bureau of Standards, 1986.
8. K. C. Clear. Measuring Rate of Corrosion of Steel in Field Concrete Structures. In *Transportation Research Record 1211*, TRB, National Research Council, Washington, D.C., 1989, pp. 28–37.

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