Highway Concrete Pavement Technology Development and Testing: Volume V—Field Evaluation of Strategic Highway Research Program (SHRP) C-206 Test Sites (Bridge Deck Overlays)

PUBLICATION NO. FHWA-RD-02-086

AUGUST 2006

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

LTPP

Foreword

Two types of concrete overlays (silica fume concrete (SFC) and latex-modified Type III portland cement concrete (LMC-III) were installed and tested as part of the Strategic Highway Research Program (SHRP) Project C-206: Optimization of Highway Concrete Technology—Bridge Deck Overlays. The two different overlay types were chosen for their ability to fill two different needs: use of SFC as a long-term, low-permeability overlay; and use of LMC-III as a high early-strength concrete for use when traffic had to be restored after as little as 24 hours. This report summarizes the 5-year study to evaluate the long-term performance of the overlays. Evaluation and comparison of SFC and LMC-III overlays were performed at four locations. The test sites were in Ohio and Kentucky. Each location included SFC and LMC-III overlays on opposite directions of a bridge structure. All overlays were installed in 1992. This study evaluated the overlays each year between 1994 and 1998. All overlays had high initial bond strengths, and the bond strengths remained high over the study period when tested away from delaminations. The overlays were generally rated as good condition in 1998, after 6 years of service, though some individual sites were rated as fair due to extensive cracking. Though good performance was achieved from both SFC and LMC-III overlays, the service life of the overlays tended to vary based on the site location. Generally, cracking and delamination of the overlays tend to increase with time. Typically, all overlays should be inspected biannually for cracking and delamination and routine maintenance including consideration of crack and delamination repairs to extend the service life of the SFC and LMC-III overlays.

Gary L. Henderson
Director
Office of Infrastructure
Research and Development

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No.
FHWA-RD-02-086

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Highway Concrete Technology Development and Testing: Volume V—Field Evaluation of Strategic Highway Research Program (SHRP) C-206 Test Sites (Bridge Deck Overlays)

5. Report Date
August 2006

6. Performing Organization Code

7. Author(s)

Stephen R. Boyd and Paul D. Krauss; Wiss, Janney, Elstner Associates, Inc.

8. Performing Organization Report No.

9. Performing Organization Name and Address
ERES Division of Applied Research
Associates Inc.
505 W. University Avenue
Champaign, IL 61820

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DTFH61-94-C-00009

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

FHWA Contracting Officer's Technical Representative: Monte Symons, P.E.
This work was conducted under subcontract by Wiss, Janney, Elstner Associates, Inc.

16. Abstract

Two types of concrete overlays (silica fume concrete (SFC) and latex-modified Type III portland cement concrete (LMC-III) were installed and tested as part of the Strategic Highway Research Program (SHRP) Project C-206: Optimization of Highway Concrete Technology—Bridge Deck Overlays. The two different overlay types were chosen for their ability to fill two different needs: use of SFC as a long-term, low-permeability overlay; and use of LMC-III as a high early-strength concrete when traffic had to be restored after as little as 24 hours. This report summarizes the 5-year study to evaluate the long-term performance of the overlays. Evaluation and comparison of SFC and LMC-III overlays were performed at four locations. The test sites were in Ohio and Kentucky. Each location included SFC and LMC-III overlays on opposite directions of a bridge structure. All overlays were installed in 1992. This study evaluated the overlays each year between 1994 and 1998. All overlays had high initial bond strengths, and the bond strengths remained high over the study period when tested away from delaminations. The overlays were generally rated as good condition in 1998, after 6 years of service, though some individual sites were rated as fair due to extensive cracking. Though good performance was achieved from both SFC and LMC-III overlays, the service life of the overlays tended to vary based on the site location. Generally, cracking and delamination of the overlays tend to increase with time. Typically, all overlays should be inspected biannually for cracking and delamination and routine maintenance, including consideration of crack and delamination repairs to extend the service life of the SFC and LMC-III overlays.

17. Key Words
Concrete pavement, high early-strength, early opening, full-depth repair

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No of Pages
80

1. Price

Form DOT F 1700.7(8-72)

Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

This volume of the report describes the investigation and evaluation of silica fume and latex-modified concrete overlays used in bridge deck rehabilitation projects. The overlays were installed as part of the Strategic Highway Research Program (SHRP) Project C-206: Optimization of Highway Concrete Technology—Bridge Deck Overlays, which is detailed in the report issued at the conclusion of that study. Two types of concrete were tested in the overlays, silica fume concrete (SFC) and latex-modified Type III cement concrete (LMC-III). The two different overlay types were chosen for their ability to fill two different needs. The use of the SFC overlay was anticipated for use as a long-term low-permeability overlay, while use of the LMC-III was foreseen as a high early-strength concrete for use when traffic had to be restored after as little as 24 hours. This report summarizes the 5-year study to evaluate the long-term performance of the overlays.

CHAPTER 2. SUMMARY OF TESTING TECHNIQUES

The four bridge deck overlay sites were visited by contractor personnel for the first time in 1994. During the visits, the test areas were laid out, corrosion testing was performed, samples were taken, and the overall condition of the overlays was determined. In most cases, these visits were used to establish a detailed initial condition of the structures, as no distress maps of the overlays were included in the original SHRP report, and only a few specific observations of the test sites were included. The primary testing performed and reported under SHRP C-206 included direct-tension bond strength testing, bond shear strength, elastic modulus, compressive strength, split-cylinder tensile strength, scaling resistance, American Association of State Highway and Transportation Officials (AASHTO) T 277 “coulomb,” and concrete temperature monitoring.

The work performed during this initial inspection included detailed visual observation and distress mapping, delamination surveying, half-cell potential surveying, linear polarization testing, chloride sampling, and shear bond testing. Available information was gathered from the State highway agencies. In the second, third, and fifth years only the detailed visual observation and distress mapping, delamination surveying, and chloride sampling were performed. In the fourth year (1997) the work performed included all of the testing performed during the initial inspection.

VISUAL SURVEY AND DISTRESS MAPPING

The distress mapping was performed in general accordance with the SHRP Long-Term Pavement Performance (LTPP) Distress Identification Manual, with modification as required to adapt the pavement-oriented manual to use for a bridge. The SHRP LTPP manual is oriented primarily towards structural distress of pavements cast on grade and does not address certain problems related to bridges. For example, the LTPP manual requires a listing of “corner breaks,” “lane-to-shoulder dropoff,” and “joint spalls,” none of which would occur in a bridge deck. Also, bridge decks frequently exhibit frequent narrow nonstructural transverse or longitudinal cracking. Although this is covered by the LTPP manual, it is far more important on a bridge deck than on a jointed pavement.

DELAMINATION SURVEYS

The delamination surveys were conducted with a chain drag supplemented by manual rodding or hammering as described in the American Society for Testing and Materials (ASTM) D 4580, Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding. In areas where the chains or rodding indicated delaminated areas, hand hammering was used to determine the extent of the delamination.

COPPER/COPPER SULFATE HALF-CELL POTENTIAL TESTING

The half-cell potential survey was performed as described in ASTM C 876, Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete, using a copper/copper sulfate reference cell and an automatic data recorder. In the test, the voltage difference between the reinforcing steel and the reference electrode is measured using a voltmeter. The measured voltage difference changes with the changing corrosion state of the reinforcing steel, allowing it to be used as an indicator of the corrosion state of the reinforcement. The test is performed by connecting the positive terminal of a high-impedance voltmeter to the reinforcing steel and the negative terminal to the reference cell. On the bridges, all of the connections to the reinforcing steel were made by coring through the concrete to the upper mat of reinforcing steel, removing the concrete around the bar with a cold chisel, and attaching to the reinforcing bar with locking pliers, an electrical clamp or by drilling and tapping into the steel. Once the connections were made, the readings were taken by holding the junction sponge of the reference cell in contact with the concrete and monitoring the observed voltage until it stabilized, at which point the voltage was recorded. At the bridges, all of the readings stabilized quickly and were reproducible within the ASTM-required 10 millivolts (mV) when re-tested. The high stability of the readings was probably due to the relatively moist condition of the concrete in the bridges, as stability is typically related to concrete moisture content.

POLARIZATION RESISTANCE (PR) TESTING

The linear polarization testing was performed using a computer-controlled potentiostat using a surface electrode assembly patterned after that used by a “3LP” commercial device. The polarization resistance technique for the determination of corrosion rates has been used by corrosion engineers for a relatively long period of time. However, it has only recently been used for more than extremely limited work in reinforced concrete. Polarization resistance uses simplified electrochemical corrosion theory to estimate corrosion rates of metals in corroding systems, using the electrical properties of the system to determine the rate of the corrosion. This is accomplished by forcing the area under test to deviate slightly (20 mV) from its equilibrium corrosion potential while measuring the electrical current required to make the change in potential. Because the specimen potential and the corrosion current are approximately linear over the small potential range measured, the measured changes in potential (ΔE) and applied current ($\Delta_{iapplied}$) and the Tafel slopes (β_a and β_c) can be used to determine the corrosion rate (i_{corr}) of the system using the following equation:

$$\frac{\Delta \mathrm{E}}{\Delta\, \mathrm{i}_{\mathrm{applied}}} = \frac{\beta_{\mathrm{a}}\, \beta_{\mathrm{c}}}{2.3\,(\mathrm{i}_{\mathrm{corr}})\,(\beta_{\mathrm{a}} + \beta_{\mathrm{c}})} \tag{1}$$

The technique is limited by the accuracy of the test data, and their interpretation. In addition, the characteristic Tafel slopes of the anodic and cathodic portions of the specimen's current versus potential relationship, β_a and β_c, must be assumed. Although the equation is relatively insensitive to the β values, and a typical assumption of 0.12 volt (V)/decade is reasonable for most steel-based systems, the resulting estimates of the corrosion current, i_{corr} can be incorrect by up to a factor of 3 or 4. Compensation is used to account for the voltage drop due to the concrete resistance (“IR compensation,” or current (I) times resistance (R)), but it is not always entirely effective. The greatest limitation of the technique is its poor performance in high-resistance media, such as dry concrete. Under those conditions, the voltage output of the potentiostat required to penetrate the concrete can overshadow the voltage required to completely polarize the metal under test, and the IR compensation may not be able to sufficiently correct for the voltage drop between the embedded metal under test and the counter and reference electrodes on the concrete surface.

Practically, the PR test is performed by first making a connection to the reinforcing steel and monitoring its potential while an external voltage is applied via a counter-electrode on the concrete surface, as shown schematically in figure 1. The test is performed by changing the voltage applied between the counter electrode and the reinforcing bars to produce the 20 mV potential shift (ΔE) between reinforcing steel and the reference cell described previously. The current ($i_{applied}$) flowing between the counter electrode and the reinforcing steel is measured and used to compute the corrosion rate using the equation shown above. In reinforced concrete, some question arises regarding the normalization of the estimated currents to a corroding area.

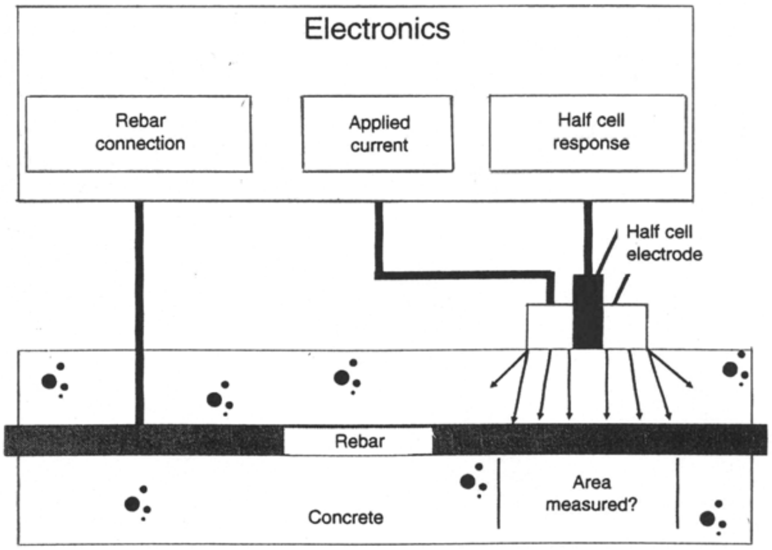


Figure 1. Schematic drawing of polarization resistance test setup.

For this work, the polarized area was assumed to be the surface area of the upper half of the bar immediately below the counter electrode. The PR scans were performed using IR compensation at each step to determine and correct for the potential drop due to the concrete resistance. The PR scans started at a potential 10 mV below the equilibrium rest potential of the area under test and continued to a potential 10 mV above the equilibrium potential. Following the testing, the polarization resistances were determined by fitting a line to the recorded potential versus current plots. Using the polarization resistances, the corrosion rates were estimated by assuming Tafel slopes of 0.12, assuming that the upper bars were size number 4, and assuming that the upper half of the reinforcing bar directly under the counter electrode was polarized during the testing.

CHLORIDE SAMPLING AND TESTING

The chloride sampling was accomplished using cores instead of drilled powder samples. The contractor has found removing cores, followed by slicing and grinding the slices, to be a more accurate method for determining concrete chloride contents than removing powder samples using a rotary impact drill. Once the samples were cut and ground, they were analyzed by either an acid- or water-soluble chloride extraction followed by a potentiometric titration.

SHEAR BOND TESTING

The shear bond testing was performed using a shear bond guillotine. All of the cores were bedded in a plaster-based material before testing to allow for uniform load applications.

INSPECTION SCHEDULE DESCRIPTION

The four bridge deck overlay sites were revisited for the annual inspections, as described in Task E, Field Evaluation of SHRP C-206 Test Sites of Project DTFH61-94-R-00009. The visits were usually in the fall. The cumulative results from the 5 years of inspections are detailed in the following sections for each individual site.

CHAPTER 3. INTERSTATE 270 (I–270) IN COLUMBUS, OH

INTRODUCTION

This site consists of two sections on twin bridges over Raymond Run in Columbus, OH. The site is located 0.8 kilometers (km) (0.5 miles (mi)) south of Roberts Road overpass over I–270. Overall views of both spans are shown in figures 2 and 3. The twin bridges are single span, 6.1 meters (m) (20 feet (ft)) long, and simply supported at the abutments. The deck is 380 millimeters (mm) (15 inches) thick.

Figure 2. Photograph showing test section on I–270 northbound (1995).

Figure 3. Photograph showing test section on I–270 southbound (1995).

The decks were originally constructed in 1969 and were covered with a 6-mm (0.23-inch) thick latex emulsified asphaltic concrete overlay. In 1991, an inspection by state forces indicated the deck to be in generally satisfactory condition with delaminations and patches over 10 percent of the deck surface. There were obvious transverse cracks in the decks. The decks were included for overlayment as part of a larger rehabilitation project (Ohio Department of Transportation (ODOT) 8753-91) that covered 4.3 km (6.9 mi) of I–270. The project included repaving and widening of the bridge structures. The northbound lanes were selected for overlay with silica fume concrete and the southbound lanes with LMC-III concrete. The I–270 site was inspected on the following dates:

- September 9, 1994.
- October 10, 1995.
- November 12, 1996.
- September 8, 1997.
- October 13, 1998.

Northbound (NB) Lanes—Project records indicate that the materials used for the SFC overlay mix consisted of: a Type I cement from a local supplier; a sub-rounded to rounded natural sand which was a mixture of siliceous and calcareous minerals having a specific gravity of 2.62, absorption of 1.54 percent, and a fine modulus (FM) of 3.36; and a crushed limestone coarse aggregate having a maximum top size of 12 mm (0.5 inch), a specific gravity of 2.62, and an absorption of 1.96 percent. The admixtures used were: Sika-Crete silica fume (slurry form); Sika AER, a neutralized Vinsol resin air-entraining agent; Plastocrete 161 MR, a Type D water reducer/retarder; and Sikament 300, a Type F high range water reducer. The mixture proportions reported for both overlays are shown in table 1. The specification on the fresh properties of the silica fume mix include a slump of 100 to 200 mm (4 to 8 inches) and an air content range of 6 to 10 percent.

Table 1. Mix proportions for LMC-III and SFC overlays (lb/yd^3).

Material (lb/y^3)	LMC-III	SFC
Cement	Type III—658	Type I—700
Fine Aggregate	1591	1470
Coarse Aggregate	1306	1292
Water	321	223
Silica Fume	-	70
Latex Modifier (gallon)	25	-
Water Reducer (ounce)	-	25
High-range water reducer (HRWR) (ounce)	-	218
Air entraining agent (AEA) (ounce)	-	5
Water-to-cement (W/C) ratio	0.48	0.29

1 ounce = 29.57 mL
1 gallon =3.785 L
1 lb/y3 = 0.347 kg/m3

Southbound (SB) Lanes—The materials used in LMC-III overlay mix included: a Type III cement; the same aggregates as the SFC mix; and a Latex, Styrofan 1186, which is a styrene-butadiene latex emulsion. The specifications for the fresh concrete were a slump range of 100 to 150 mm (4 to 6 inches) and an air content not to exceed 7 percent.

The asphalt overlay was removed and the surface scarified in preparation for placement of the overlays. Both overlays were placed on May 27, 1992. The SFC was placed first on the passing lane of the northbound deck. Two 3.82-m^3 (5-y^3) batches were delivered. The deck was wetted 1 hour prior to placement of the overlay. The placement went smoothly with no reported problems. The surface was textured with steel tines transversely on 16 mm (0.6 inch) centers, then covered with wet burlap and polyethylene sheeting and continuously soaked for a period of 48 hours. The LMC-III overlay was placed the afternoon of the same day on the passing lane of the southbound deck. Placement appeared to go smoothly, however the state inspectors questioned the calibration of the mobile mixer during the pour. Improper calibration led to higher amounts of water being used than desired. Calculations showed the water to cement ratio was actually 0.48 in the mix. The same texture was applied to this overlay and it was then moist cured for 48 hours under soaked burlap. Both sections were opened to traffic on June 19, 1992.

VISUAL INSPECTION

The undersides of the two bridges were inspected annually as traffic control was being set up. The structures have no girders or thickened beam portions, but have flat undersides. Some fine cracking was observed on the underside but no efflorescence staining was seen on the underside of either span. No corrosion staining occurred at the crack locations. Some leakage was apparent at the joint between the bridge decks and the abutments. The drains in the abutment headwalls were functioning, with water flowing. A cold joint could be seen on the deck bottom and in the abutment where the bridge had been widened. The only other feature of note was rust staining at the exposed bar chair tips on the underside of the deck.

The test sections studied on both spans include the shoulder and travel (outside) lanes. Examination of the deck overlay surface indicated several narrow longitudinal cracks in the shoulder lanes of both bridges. Cracks were more frequent in the travel lanes. The travel lane of the northbound SFC bridge had mostly single nonconnected cracks running in both the longitudinal and transverse directions with very little branching. The travel lane of the southbound LMC bridge had more and longer longitudinal cracks and also more branching of cracks.

Severe cracking and spalling was noted in the exposed travel surfaces of the abutments of the northbound SFC structure. The overlay at the approach joint was spalled away and had been patched with a soft tar-like material. The joint between the bridge and the abutment on the leave side of the bridge was irregular, with a separate one-foot wide closure pour placed between the deck and the abutment. The joint between the closure pour and the abutment was well-sealed, but the formed joint between the deck and the closure pour was open and packed with debris.

DELAMINATION SURVEY

The chain drag and hammer survey technique was used to locate areas of delamination of the overlay from the original concrete deck. Delaminations were found mostly at crack locations. The chain drag was used to initially find the delaminations. They were then more clearly delineated using hammer tapping and loose sand. Table 2 shows the number and areas of delaminations located on the northbound SFC bridge. The area of the northbound test section is 37.2 m^2 (400 ft^2). The number of delamination areas has increased over the last five years from 0 in 1994 to 6 in 1998. All the delaminations are in the travel lane and are isolated from each other. The largest single delamination area in 1998 is 1.16 m^2 (13 ft^2). The total area of delaminations is 2.46 m^2 (26.5 ft^2) or 6.61 percent of the test area and is not considered a serious amount.

Table 2. Number and areas of delaminations (I–270 northbound SFC).

Year	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	0	0.00	0.00
1995	2	0.14	0.38
1996	3	0.93	2.50
1997	4	1.48	3.98
1998	6	2.46	6.61

Table 3 shows the number and areas of delaminations located on the southbound LMC bridge. The area of the southbound test section is 40.9 m^2 (440 ft^2). There are the same number of delaminations on this bridge (six) as on the northbound bridge but the total area is slightly more at 2.87 m^2 (31.9 ft^2) or 7.02 percent of the test area. The largest single area of delamination is 0.56 m^2 (6.0 ft^2) but there are two that size and three others slightly smaller. Again all the delaminations are in the travel lane. Some delaminated areas are connected by longitudinal cracks which may be a precursor to further delamination.

Table 3. Number and areas of delaminations (I–270 southbound LMC).

Year	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	0	0.00	0.00
1995	2	0.46	1.12
1996	4	0.93	2.27
1997	6	1.25	3.06
1998	6	2.87	7.02

HALF-CELL POTENTIAL SURVEY

The half-cell potential survey was performed using a 0.6-m (2-ft) grid spacing over the entire test area (shoulder and outside travel lane) of each span in 1994 and 1997. The electrical connection to the top layer of reinforcement was made using a 50-mm (2-inch) diameter core hole drilled to the top layer of reinforcing steel. A hole was drilled in the reinforcing bar and a self-tapping screw was used to make the connection. The half-cell readings for the northbound lanes SFC in 1994 ranged from –179 mV to –471 mV, with large potential differences between nearby areas. These readings tend to indicate that some corrosion is taking place in the bridge. Table 4 shows the cumulative frequency of the half-cell potentials for the northbound SFC structure in 1994. Table 5 shows the cumulative frequency of the half-cell potentials measured in 1997. These numbers range from –133 mV to –535 mV. A histogram of the data for the I–270 northbound SFC structure for 1994 and 1997 is shown in figure 4. The potentials tend to be less negative in 1997 than in 1994, however, many areas remain very negative, indicating continued corrosion.

An equipotential map for the northbound SFC test section in 1997 is shown in figure 5. The most negative potentials were seen at the ends of the bridge and near the cracked delaminations. No area of more negative potentials was associated with the longitudinal construction joint. Approximately three-quarters of the readings were more negative than –250 mV, indicating that corrosion is likely occurring over most of the deck. The alignment of the areas of rapid potential changes with the edges of the bridge and the cracked delaminations indicate that the overlay is not providing sufficient protection from water and waterborne chlorides in these locations.

Table 4. Cumulative percent of half-cell potentials for I–270 NB in 1994 (silica fume-modified).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –149	0	0.0
–150 to –199	3	2.5
–200 to –249	14	14.2
–250 to –299	21	31.7
–300 to –349	35	60.8
–350 to –399	25	81.7
–400 to –449	16	95.0
–450 to –499	6	100.0
–500 to –549	0	100.0

Table 5. Cumulative percent of half-cell potentials for I–270 NB in 1997 (silica fume-modified).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –149	3	2.8
–150 to –199	7	9.3
–200 to –249	16	24.1
–250 to –299	23	45.4
–300 to –349	28	71.3
–350 to –399	15	85.2
–400 to –449	11	95.4
–450 to –499	3	98.2
–500 to –549	2	100.0

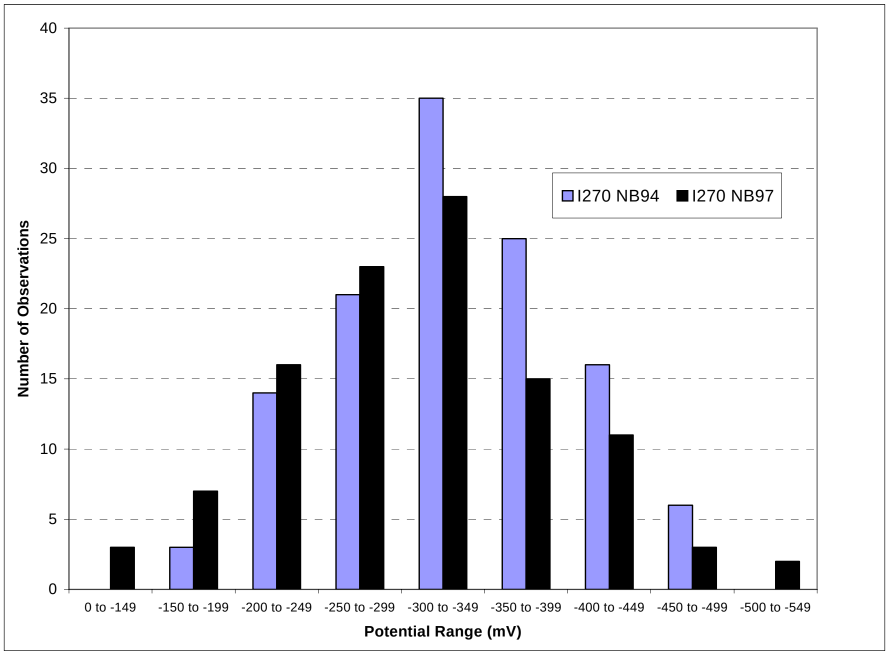
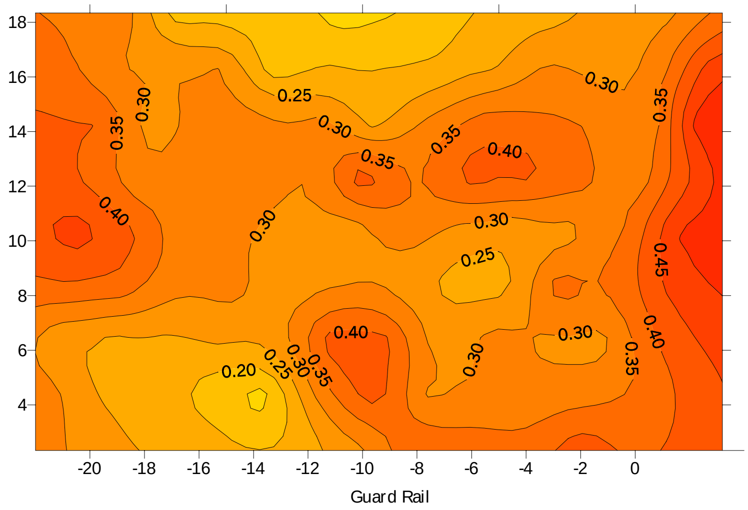


Figure 4. Histogram of half-cell potentials for I–270 NB SFC test section for 1994 and 1997.



Traffic Direction ⟶

Figure 5. Equipotential map of half-cell potentials for I–270 NB (silica fume-modified concrete).

The half-cell potentials for the southbound LMC span in 1994 range from –188 mV to –540 mV. A cumulative percentage summary of the data is shown in table 6. The data for 1997 is shown in table 7. For 1997 the data ranges from –167 mV to –449 mV. A histogram of the data for the southbound LMC test section for the years 1994 and 1997 is shown in figure 6. The potential generally shift less negative (less corrosion) in 1997 versus 1994.

Table 6. Cumulative frequency of half-cell potentials for I–270 SB in 1994 (latex-modified).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –149	0	0.0
–150 to –199	1	0.8
–200 to –249	1	1.7
–250 to –299	8	8.3
–300 to –349	30	33.3
–350 to –399	38	65.0
–400 to –449	30	90.0
–450 to –499	10	98.3
–500 to –549	2	100.0

Table 7. Cumulative frequency of half-cell potentials for I–270 SB in 1997 (latex-modified).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –149	0	0.0
–150 to –199	2	1.5
–200 to –249	15	13.1
–250 to –299	35	40.0
–300 to –349	40	70.7
–350 to –399	28	92.3
–400 to –449	10	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

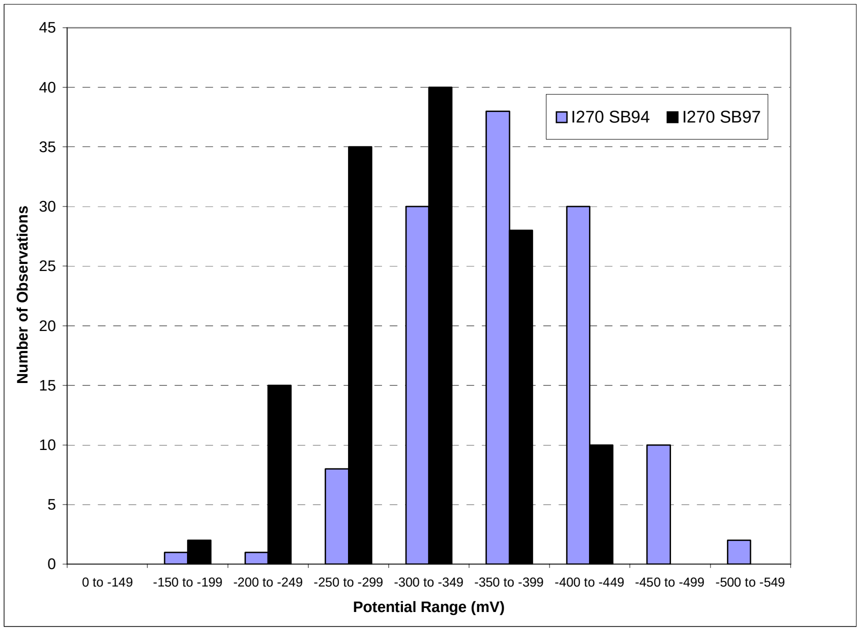


Figure 6. Histogram of half-cell potential readings for the I–270 southbound LMC-III test section for 1994 and 1997.

An equipotential map of the half- cell data for the I–270 southbound test section in 1997 is shown in figure 7. The most negative potentials were seen in the areas of the construction joint, the ends of the bridge, and near cracked delaminations. The majority of the readings were more negative than –250 mV. Also, indicative of corrosion in the structure are the relatively large differences in potential across the area surveyed, as indicated by the closely spaced lines on the contour plot. The most negative potentials along the edges of the bridge, the construction joint, and the cracked delamination indicate that the overlay is not providing sufficient protection from water and waterborne chlorides in these locations.

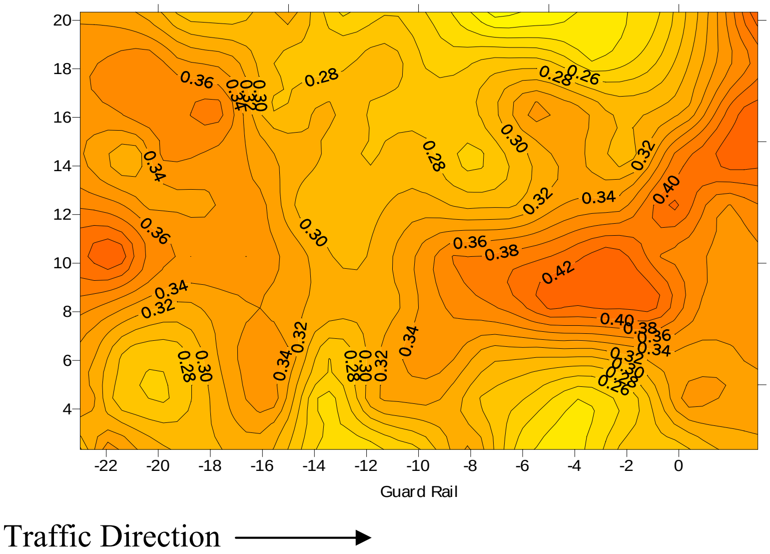


Figure 7. Equipotential map of half-cell potentials for I–270 southbound (latex-modified concrete).

Past experience with research performed at the contractor site and published in FHWA report FHWA-RD-86-193, *Protective Systems for New Prestressed and Substructure Concrete*, indicates that corrosion potentials more negative than approximately –230 mV indicate that corrosion is taking place in bridge deck type structures. According to the –230 mV criteria, the majority of the locations surveyed had potentials indicating that corrosion was taking place. Both structures appear to be undergoing corrosion over the majority of their deck area. The ends of the bridges and the areas under cracked delaminations appear to be especially vulnerable. A cumulative frequency diagram of the potentials is shown in figure 8. The curve for both bridge decks is shifted to the left from 1994 to 1997. This indicates a decrease in the overall half-cell potentials. The shift is larger for the southbound lanes which have the latex-modified overlay.

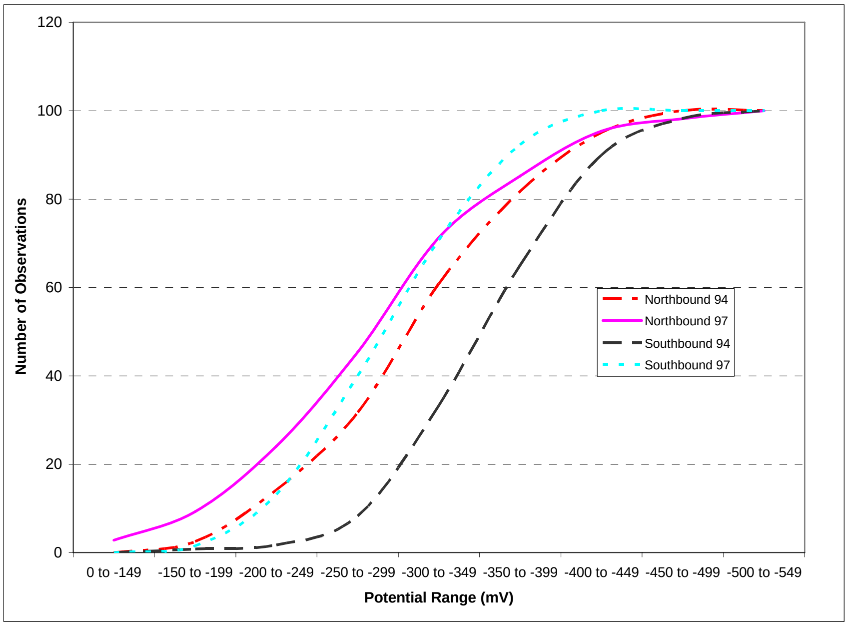


Figure 8. Cumulative frequency diagram for I–270 (NB and SB) for years 1994 and 1997.

POLARIZATION RESISTANCE (PR) TESTING

In 1994, polarization resistance (PR) tests were performed at six locations on the northbound SFC bridge. The test locations were chosen from one low-potential area and five high-potential areas. Simulated 3LP tests were also performed at each of the test locations. The PR testing was generally more successful than the 3LP testing, with five of the six locations being successfully tested. Only three of the six locations were successfully tested using the 3LP technique. The results are summarized in table 8.

The corrosion rate measurements were in general agreement with the half-cell potential measurements, with the most negative potentials associated with the highest corrosion rates. The location with the least-negative potential, point B8, could not be successfully measured using either the polarization resistance or the 3LP technique. This matches previous experience where low corrosion rate areas are difficult to measure using these techniques. The difficulties may also be due to the high electrical resistance of the SFC overlay. Silica fume is well known for its ability to increase the electrical resistance of concrete, one of the reasons for the very low AASHTO T 277 "coulomb" values produced by silica fume concretes.

Table 8. Corrosion rate testing on I–270 northbound SFC (1994).

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
H12	–355	300	0.072	-	-
G12	–400	647	0.034	188	0.116
B8	–205	-	-	-	-
C6	–451	121	0.179	149	0.145
G5	–439	157	0.138	-	-
F3	–395	320	0.068	331	0.066

* Measured using a Cu/CuSO4 reference electrode.

Polarization resistance tests were also performed at six locations on the southbound LMC bridge in 1994. The test locations were chosen from one medium-potential area and five high-potential areas. The PR and 3LP testing was generally more successful on the southbound LMC structure than on the northbound SFC structure, with all six locations being successfully tested using both techniques. The results of the testing are summarized in table 9.

Table 9. Corrosion rate testing on I–270 southbound LMC (1994).

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
G11	–497	337	0.058	991	0.021
C11	–332	261	0.083	711	0.031
A9	–336	193	0.109	469	0.046
C7	–411	346	0.063	1081	0.020
B5	–269	456	0.048	1123	0.019
F4	–536	252	0.086	322	0.068

* Measured using a copper/copper sulfate (Cu/CuSO4) reference electrode.

On the southbound LMC structure, the corrosion rate measurements were not in general agreement with the half-cell potential measurements, as was seen on the northbound structure. On the southbound structure, the highest corrosion rates did not necessarily correspond to the most negative potentials. The agreement between the corrosion rates estimated using the two techniques was encouraging, as all of the estimates were within a factor of two or three, which is considered good using these techniques.

In 1997, linear polarization measurements were performed on both spans at locations with high, medium, and low corrosion potentials. The testing was performed using a James Instruments GECOR 6 Polarization Resistance Tester. The equipment uses a confinement ring to delineate the area under test. For comparison, tests were also performed using an EG&G PARC Model 270A potentiostat under computer control, as was performed during the initial 1994 tests. The test equipment performed poorly on the southbound LMC side, with the current frequently unconfined and the readings erratic. Readings for which the signal was not fully confined are suspect because the area under test is unknown and cannot be compensated for. The results of the testing for both the northbound and the southbound structures are shown in table 10.

Table 10. Results of polarization resistance testing at I–270 (1997).

Direction	Grid Location	Half-Cell Potential (mV)	Measured Corrosion Rate ($\mu A/cm^2$)	Notes
Southbound LMC	D2	–374	0.725	Not fully confined, corrosion rate measured as 0.604 $\mu A/cm^2$ using EG&G PARC equipment
	A3	–197	2.759	Not fully confined
	E13	–338	0.055	Not fully confined
	B11	–199	0.022	Not fully confined
Northbound SFC	H16	–176	0.052	Prewet
	H16	–222	0.110	Prewet
	B16	–149	0.131	Prewet
	B16	–133	1.293	Prewet, not fully confined
	C12	–421	1.184	Uncracked, not fully confined
	G22	–468	0.630	At a crack, prewet
	G22	–390	0.044	Near joint
	B10	–421	0.202	Near bond core, wet from coring
	F4	–384	0.182	After coring
	F4	–385	2.578	Repeat of previous test, not fully confined
	F4	–396	0.441	Same location as Point F4 above, but opposite side of core hole
	F12	–430	0.789	After coring
	F12	–418	0.516	Adjacent bar
	F10	–441	0.491	Surface dry
	B14	–250	0.442	Not fully confined, surface dry

SHEAR BOND TESTING

In 1994, three of the cores removed from the southbound structure and four of the cores removed from the northbound structure were tested to determine their bond strength in direct shear. The overlay thicknesses measured ranged from 25 to 102 mm (1 to 4 inches). The observed clear cover over the bars ranged from 76 to 102 mm (3 to 4 inches). The results of the testing are shown in table 11.

Table 11. Shear bond testing of cores from I–270 (1994).

Structure / Overlay Type	Core ID	Bond Strength MPa (psi)	Failure Location (percent of failure area)		
			Overlay	Bond Line	Substrate
Northbound Silica fume	N2	3.16 (459)	5	0	95
	N4	4.09 (593)	15	0	85
	N8	4.52 (656)	15	0	85
	N9	3.42 (496)	15	0	85
Southbound LMC-III	S6	3.32 (481)	5	5	90
	S7	4.72 (684)	20	0	80
	S8	4.76 (691)	10	0	90

The average bond strength for the northbound SFC cores was 3.79 megapascal (MPa) (551 pounds per square inch (psi) and for the southbound LMC cores was 4.27 MPa (619 psi). The failure strengths of the two overlays were similar. This is to be expected as both failed primarily in the substrate concrete, which was nominally the same in both concretes. The failure of the cores primarily in the substrate concrete indicates that the surface preparation and application was excellent for these two overlays, as improper installation or poor surface preparation will typically result in failures at the bond line, with the substrate concrete left intact.

The shear bond testing results for 1997 are shown in table 12. The average bond strength for the northbound SFC cores is 5.8 MPa (840 psi) and for the southbound LMC cores is 4.83 MPa (700 psi). The failure locations were primarily within the base concrete. These results indicate that the bond between the overlay and the substrate remains good.

Table 12. Shear bond testing of cores from I–270 (1997).

Structure / Overlay Type	Core ID	Exposure	Bond Strength MPa (psi)
Northbound Silica Fume	N1	Wheelpath, near delamination	3.6 (520)
	N2	Wheelpath	9.1 (1320)
	N3	Wheelpath	6.2 (900)
	N7	Shoulder	4.3 (620)
Southbound LMC-III	S1	Wheelpath	4.1 (600)
	S2	Shoulder	4.6 (670)
	S3	Centerline	5.7 (830)

CHLORIDE ANALYSES

Chloride analyses were performed on six cores from each overlay in 1994. The samples were taken from the 13- to 25-mm (0.5- to 1-inch) depth surface region and from the 95- to 102-mm (3.75- to 4-inches) depth where the reinforcing bars are typically located. All of the slices were pulverized and analyzed to determine their acid-soluble chloride content. In addition to the acid-soluble chloride analyses, water-soluble chloride analyses were performed on selected samples. The results of the testing are shown in table 13.

Table 13. Results of chloride content testing of cores from I–270 (1994).

Structure / Overlay Type	Sample Number	Acid-Soluble Chloride Content, percent by concrete weight		Water-Soluble Chloride Content, percent by concrete weight	
		0.5 to 1 inch	3.75 to 4 inches	0.5 to 1 inch	3.75 to 4 inches
Northbound Silica fume	N1	0.017	0.075	-	-
	N3	-	0.129	-	-
	N5	-	0.076	-	-
	N6	-	0.095	-	-
	N7	0.018	0.039	-	-
	N8	-	0.018	-	-
Southbound LMC-III	S2	-	0.046	-	0.032
	S3	0.048	-	-	0.032
	S4	-	0.045	-	0.025
	S5	-	0.093	-	-
	S7	-	< 0.007	-	-
	S9	0.041	0.034	-	-

All of the locations had moderate to high chloride concentrations at the level of the reinforcing bars, except for sample S7 and N8. The threshold for chloride-induced corrosion of black reinforcing steel is approximately 0.025 percent by concrete weight, so most of the locations in the deck appear to have sufficient chloride to support corrosion. This agrees with the indication of corrosion given by the half-cell potential and corrosion rate readings. The chloride analyses for the overlays in 1998 are shown in table 14. Two samples were taken from each structure. Chlorides in the near surface of the overlays tend to be higher in the LMC concrete than in the SFC concrete. Except for one core from the LMC that had high chlorides throughout its depth, chlorides typically decrease to moderately low levels at the 15.9 to 25.4 mm (0.625 to 1 inch) depth

Table 14. Results of chloride content testing of cores from I–270 (1998).

Overlay Type	Sample Number	Acid-Soluble Chloride Content, percent by concrete weight			
		0.25 to 0.5 inch	0.625 to 1 inch	1.125 to 1.5 inches	3.75 to 4 inches
Northbound	N1	0.210	0.032	0.019	0.059
Silica fume	N2	0.065	0.034	0.020	0.023
Southbound	S1	0.278	0.202	0.218	0.094
LMC-III	S2	0.208	0.065	0.021	0.050

SUMARY OF I–270 TESTS (COLUMBUS, OH)

The SFC and LMC-III overlays were placed in May 1992. Overall, the overlays were in good condition in 1998. Each overlay had some cracking and delaminations increased for zero to six locations between 1994 and 1998. The total area of delamination was moderate and about 2.5 m^2 (26.9 ft^2) SFC and 2.9 m^2 (31.2 ft^2) LMC-III in 1998. This represents 6.6 percent SFC and 7 percent LMC-III of the total deck area. Delaminations have been increasing in a linear or slightly exponential manner since 1994. Shear load tests indicate that the nondelaminated areas maintain high bond strength for both overlays. The percentages of half-cell potentials more positive than

–250mV ($CuCuSO_4$) are presented in table 15. The potential data indicate that corrosion of the embedded steel is likely over three-quarters of each deck but that the potentials have shifted slightly more positive (less corrosive) with time.

Table 15. Potentials more positive than –250mV ($Cu/CuSO_4$) (percent of measurements).

Year	NB (SFC)	SB (LMC-III)
1994	14.2	1.7
1997	24.1	13.1

Corrosion rates of the embedded reinforcing were measured in 1994 and in 1997 using various techniques. Difficulties in measuring the corrosion rates through the overlays were encountered. The rates varied from low to high values. Corrosion of areas of both decks continues. The chloride ion content in the original deck concrete at the level of the reinforcing steel is sufficient to cause corrosion of mild steel. Redistribution of this chloride with time has occurred and is expected. Chloride has also penetrated into the surface of the overlays in large amounts. Future corrosion and possibly continued delamination or other distress should be anticipated on this bridge.

CHAPTER 4. U.S. 52 IN NEW RICHMOND, OH

INTRODUCTION

This site consists of two medium-length (68 m (225 ft)) three-span parallel bridges carrying U.S. 52 over Twelve Mile Creek just west of the town of New Richmond, OH. The bridges consist of concrete decks on continuous structural steel I-beams and cross-frames. The two end spans are 22 m (71 ft) long, while the center span is 25 m (82 ft) long. The bridges were originally constructed in 1965, and in 1991 were reported to be in "satisfactory" condition, with delaminations and patches over approximately 20 percent of the surface. The overlays were placed as part of a larger project to extend U.S. 52 to meet I–275 in Cincinnati. The eastbound deck shown in figure 9, and the westbound travel lane shown in figure 10, were overlaid with LMC-III concrete, while the westbound passing lane shown in figure 11 was overlaid with a SFC overlay. The original information provided to the researchers incorrectly indicated that the westbound travel lane was overlaid with SFC.

The U.S. 52 test site was inspected on:

- September 20, 1994.
- October 3, 1995.
- September 17, 1996.
- September 9, 1997.
- October 10, 1998.

Figure 9. Photograph showing the eastbound deck of U.S. 52 over Raymond Run in Columbus, OH. The overlay is latex-modified.

Figure 10. Photograph of westbound travel lane of U.S. 52 over Raymond Run in Columbus, OH. The overlay is latex-modified.

Figure 11. Photograph showing westbound passing lane of U.S. 52 over Raymond Run in Columbus, OH. The overlay is silica fume concrete.

<u>Eastbound Lanes and Westbound Travel Lane</u>—The materials selected for the LMC-III mix consisted of: a Type III cement; an angular to rounded natural sand consisting of a mixture of siliceous and calcareous minerals having a specific gravity of 2.68, absorption of 1.16 percent, and fineness modulus of 2.67; and a partially crushed limestone coarse aggregate having a maximum top-size of 12 mm (0.5 inch) with a specific gravity of 2.63 and an absorption of 2.09 percent. The latex used was DPS Modifier A, a styrene-butadiene latex emulsion. The specifications on the fresh concrete required a slump between 100 to 150 mm (4 and 6 inches) and an air content not to exceed 6 percent.

<u>Westbound Passing Lane</u>—A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: (1) Densified Microsilica

(compacted powder form); (2) Amex-210, a benzyl-sulfonate based air-entraining agent; (3) Hy-Kon 2000R, a Type D water-reducer/retarder; and (4) Hy-Con Super, a Type F high-range water reducer. The specifications on the fresh properties of the concrete include a slump of 100 to 200 mm (4 to 8 inches) and an air content range of 6 to10 percent. The mixture proportions and plastic concrete characteristics for both overlays, as reported in the C-206 report, are shown in table 16.

Table 16. U.S. 52 concrete proportions and characteristics.

Material	LMC-III	SFC
Cement (lb/yd^3)	658 (Type III)	700 (Type I)
Fine agg. (lb/yd^3)	1703	1480
Coarse agg. (lb/yd^3)	1333	1297
Water (lb/yd^3)	238	285
Latex modifier (gal/yd^3)	24.5	-
Silica fume (lb/yd^3)	-	70
Water reducer (oz/yd^3)	-	14
HRWRA (oz/yd^3)	-	175
AEA (oz/yd^3)	-	28
W/C ratio	0.36	0.37
Air content (percent)	5.2	9.5
Slump (inches)	5.5	6.5
Temperature (°F)	72	74
Unit weight (lb/ft^3)	145.4	139.4
Placement date	4/23/92	4/23/92
Weather conditions	Clear	Clear

1 lb/yd^3 = .347 kg/m^3
1 gal/yd^3 = 5 l/m^3
1 oz/yd^3 = .037 kg/m^3

1 inch = 25.4 mm
(°F - 32/1.8) = °C
1 lb/ft^3 = 16 kg/m^3

The LMC-III overlay was placed using two mobile concrete mixers. The deck was wetted 1 hour prior to placement of the overlay and a cement-sand grout was scrubbed into the deck immediately prior to placement of the overlay. The surface was textured with steel tines and covered with wet burlap and polyethylene sheeting and kept wet for 72 hours. The SFC overlay was placed later the same day. A cement-sand grout was scrubbed into the deck immediately prior to placement of the overlay. The overlay was moist-cured for 72 hours after placement in a similar manner to the LMC-III overlay. Both sections were opened to traffic on April 29, 1992.

VISUAL INSPECTION

The underside of the two bridges were inspected during the setup of the lane closure. The three span structures are supported by continuous steel girders. Both structures had been widened previously because the outermost girder (supporting the right shoulder and curb) is supported on single slender columns placed next to the original piers. The original portion of the deck underside had transverse cracks on 2.5-m (8-ft) centers, with the cracks occasionally showing some efflorescence. The outside widened portion of the deck had underside transverse cracks on

1.2-m (4-ft) centers, with the cracks near the abutments showing some efflorescence staining. Mud and silt staining on the girders, along with conversations with ODOT personnel, revealed that the structure had been under water during heavy regional floods of 1995-1996.

Eastbound Travel and Passing Lanes—Both the travel and passing lanes on this structure have the latex-modified concrete overlay. Significant change was not seen in the condition of the overlay on this structure over the time of the inspections. The predominant feature of the visual inspection was short transverse cracks filled and covered with an acrylic-like material or an opaque white resinous material. Also there were some small transverse cracks that were unsealed. Most transverse cracks were along the edges of the deck structure. Areas of concentrated longitudinal cracks were seen, with more cracking on the two end spans than on the center span. The travel lanes were more affected than the shoulders. The cracks were short and of various widths. They appeared to be caused by plastic shrinkage.

Westbound Travel Lane—This lane also has the latex-modified concrete overlay. There is some plastic cracking throughout the lane. There are several transverse cracks up to 1.2 m (4 feet) long extending from the barrier side of the lane. Overall, the latex modified overlay was in visually good condition.

Westbound Passing Lane—This lane has the silica fume concrete overlay. Cracking in this lane is less than in the other three lanes. There are some scattered plastic cracks and some short transverse cracks extending from the edge on the shoulder side of the lane. An area of rough, open finish was noted in the last (leave) third of the bridge.

DELAMINATION SURVEY

Chain drag and hammer survey techniques were used to locate and delineate areas of delamination of the overlay concrete from the original concrete deck. Delaminations were found mostly at crack locations. The number and total area of delaminations on the U.S. 52 bridge are shown in tables 17, 18, and 19. The eastbound travel lane LMC had no delaminations. The next best lane was the westbound travel lane LMC with three delaminated areas in 1998 totaling 0.37 m^2 (4 ft^2). The eastbound passing lane had only three areas totaling 0.84 m^2 (9 ft^2) in 1988.

The section with the most delaminations is the westbound passing lane SFC with seven areas and a total area of 2.16 m^2 (23.2 ft^2). All of the delaminations on this lane were associated with cracks within the delamination area. The percent delaminated area is shown in the tables. The total surface area of the passing lanes are 249 m^2 (2,680 ft^2) and for the travel lanes and shoulders are 456 m^2 (4,900 ft^2). It appears that the silica fume concrete overlay is performing slightly worse than the latex modified overlay but the silica fume overlay only has delaminations over only 0.87 percent of the surface which is very low. Generally both overlays are performing well with minimal delaminations.

Table 17. Number and areas of delaminations LMC (eastbound passing U.S. 52).

Year	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	0	0	0
1995	0	0	0
1996	3	0.84	0.34
1997	3	0.84	0.34
1998	3	0.84	0.34

Table 18. Number and areas of delaminations LMC (westbound travel U.S. 52).

Year	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	0	0	0
1995	0	0	0
1996	1	0.14	0.03
1997	1	0.14	0.03
1998	3	0.37	0.08

Table 19. Number and areas of delaminations SFC (westbound passing U.S. 52).

Year	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	0	0	0
1995	Not tested	Not tested	Not tested
1996	3	0.60	0.24
1997	3	0.60	0.24
1998	7	2.16	0.87

HALF-CELL POTENTIAL SURVEY

The half-cell potential surveys were performed using a grid marked on 0.6-m (2-ft) centers. The travel lanes were numbered starting with Row 1 at the leave end of the bridge, with the "A" grid line near the stripe separating the travel and passing lanes and the “J” line 0.6 m (2 ft) from the shoulder barrier rail. The longitudinal rows of points were numbered from 1 to 114 from the leave side to the approach side. Rows G, H, I, and J on the shoulder were not surveyed as they were reinforced with epoxy-coated reinforcing steel during the widening and all locations initially produced erratic half-cell potentials all more positive than –0.100 V. The readings for the eastbound travel lane LMC in 1994 range from approximately –0.008 V to –0.386 V. Table 20 shows that over 98 percent of the readings were less negative than –0.250 V.

The readings for the eastbound travel lane in 1997, shown in table 21, range from –0.089 V to -0.412 V. Over 97 percent of the readings are below –0.250 V. A histogram for the eastbound travel lane in 1994 and 1997 is shown in figure 12. The half-cell readings for the westbound travel lane LMC in 1994 are shown in table 22 and in a histogram in figure 13. The readings ranged from –0.001 V to –0.307 V, and table 22 indicates 99 percent are below 0.25 V. This is similar to the eastbound LMC data and indicates a small probability of scattered corrosion occurring in the westbound travel lane.

Table 20. Cumulative frequency of half-cell potentials for U.S. 52 EB travel in 1994 LMC.

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –49	5	0.7
–50 to –99	100	15.6
–100 to –149	385	72.9
–150 to –199	123	91.2
–200 to –249	48	98.4
–250 to –299	8	99.6
–300 to –349	1	99.7
–350 to –399	2	100.0
–400 to –449	0	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

Table 21. Cumulative frequency of half-cell potentials for U.S. 52 EB travel in 1997 LMC.

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –49	0	0.0
–50 to –99	5	0.8
–100 to –149	269	40.8
–150 to –199	298	85.2
–200 to –249	81	97.3
–250 to –299	15	99.6
–300 to –349	1	99.7
–350 to –399	1	99.8
–400 to –449	1	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

Table 22. Cumulative frequency of half-cell potentials for U.S. 52 for WB travel in 1994 LMC.

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –49	20	2.6
–50 to –99	457	61.0
–100 to –149	242	91.9
–150 to –199	41	97.2
–200 to –249	14	99.0
–250 to –299	7	99.9
–300 to –349	1	100.0
–350 to –399	0	100.0
–400 to –449	0	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

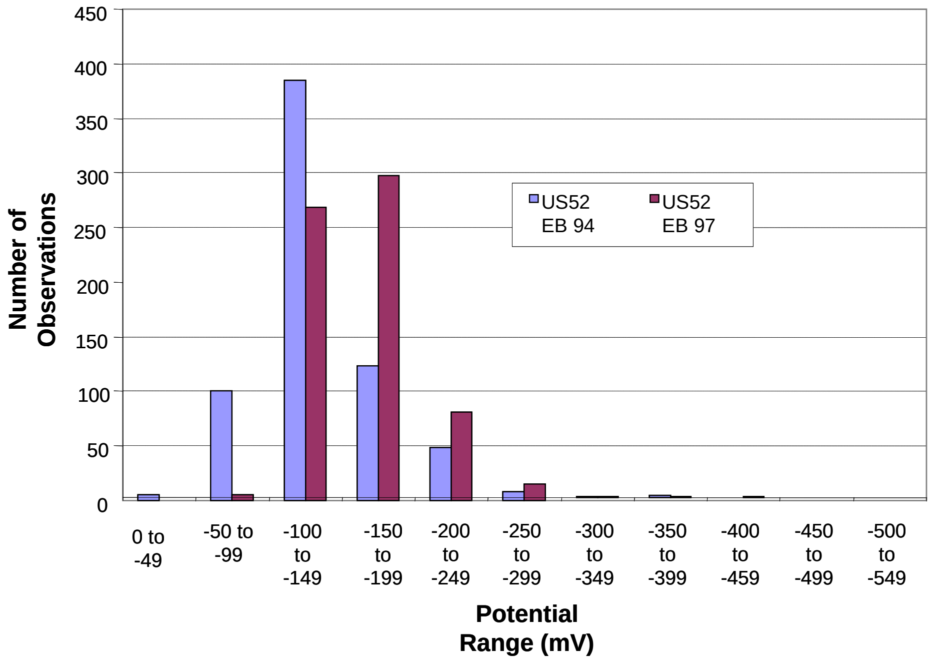


Figure 12. Histogram of half-cell potential readings for U.S. 52 eastbound travel lane LMC in 1994 and 1997.

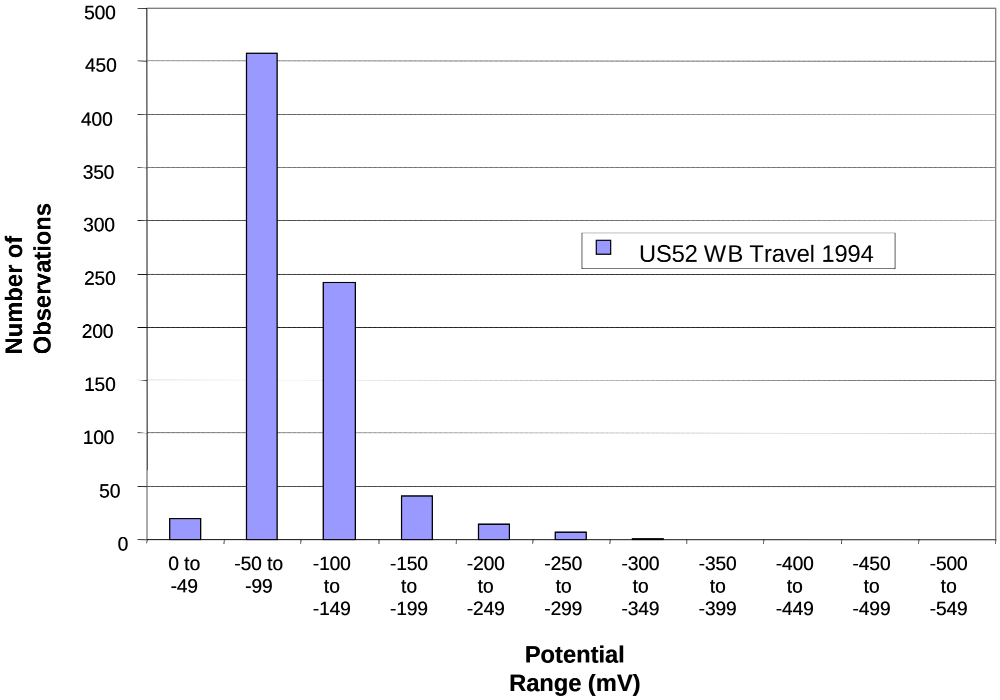


Figure 13. Histogram of half-cell potentials for U.S. 52 westbound travel lane LMC in 1994.

The westbound passing lane SFC was studied in detail in 1997 after it was discovered that it is the only lane with the silica fume overlay. It was not studied in 1994. The corrosion potential readings shown in table 23 range from –0.065 V to –0.360 V and almost 97 percent of the readings are less than –0.250 V. A histogram of the readings for westbound passing lane SFC is shown in figure 14. The SFC data is similar to the LMC data and indicates a low probability of corrosion.

Table 23. Cumulative frequency of half-cell potentials for U.S. 52 for WB passing in 1997 SFC.

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –49	0	0.0
–50 to –99	34	3.8
–100 to –149	590	69.7
–150 to –199	171	88.8
–200 to –249	71	96.8
–250 to –299	21	99.1
–300 to –349	7	99.9
–350 to –399	1	100.0
–400 to –449	0	100.0
–450 to –499	0	100.0
–500 to -549	0	100.0

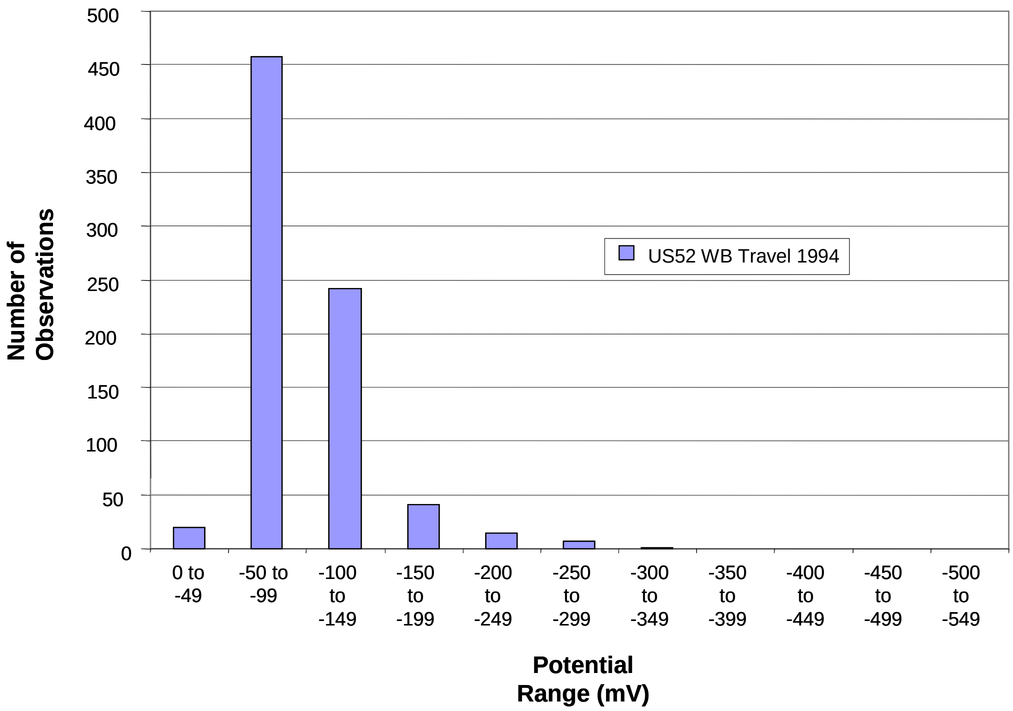


Figure 14. Histogram of half-cell potentials for U.S. 52 westbound passing lane SFC in 1997.

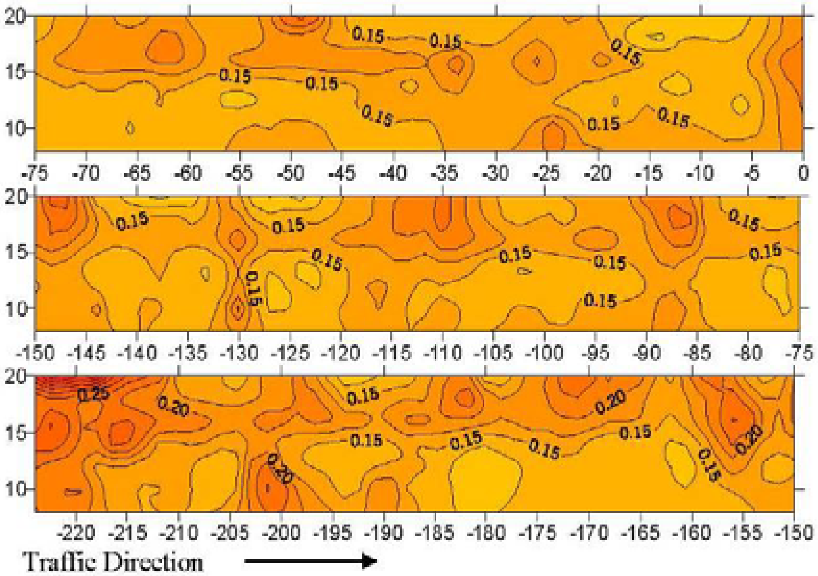


Figure 155. Equipotential map of half-cell potentials for eastbound travel lane U.S. 52 in 1997 (latex-modified concrete).

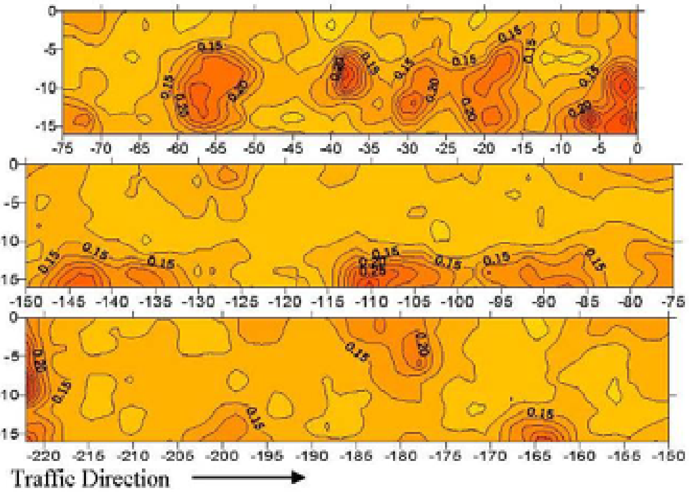


Figure 16. Equipotential map of half-cell potentials for westbound passing lane of U.S. 52 in 1997 (silica fume concrete).

POLARIZATION RESISTANCE (PR) TESTING

Polarization resistance tests were performed at five locations on the eastbound bridge and four locations on the westbound bridge in 1994. All nine locations were located in the travel lanes. At the time it was thought the westbound travel lane had a silica fume concrete overlay and the eastbound travel lane had a latex-modified concrete overlay but it was discovered both travel lanes had a latex-modified overlay. The test locations on the eastbound travel lane were chosen from two low-potential areas (–0.109 V and –0.115 V), one moderate-potential area (–0.130 V), and two high-potential areas (–0.224 V and –0.200 V). Simulated 3LP tests were also performed at each of the test locations. The PR testing was slightly more successful than the 3LP testing, with four of the five locations being tested successfully. Only three of the five locations were successfully tested using the 3LP technique. One test spot could not be successfully tested using either technique. The results of the testing are summarized in table 24. The corrosion rate measurements were generally low.

Table 24. Corrosion rate testing on U.S. 52 eastbound travel lane, LMC-III (1994).

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
B110	–0.224	-	-	-	-
B19	–0.109	339	0.064	200	0.108
C10	–0.115	429	0.050	417	0.052
C20	–0.130	232	0.093	517	0.042
D110	–0.200	449	0.048	-	-

*Measured using a $Cu/CuSO_4$ reference electrode.

The test locations on the westbound travel lane were chosen from two medium-potential areas and two low-potential areas. Simulated 3LP tests were also performed at each of the test locations. The

PR and 3LP testing was generally successful on the westbound structure, with all four locations being successfully tested using both techniques. The results of the testing are summarized in table 25.

Table 245. Corrosion rate testing on U.S. 52 westbound travel lane, LMC-III (1994).

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
B100	–0.135	395	0.055	174	0.125
C110	–0.146	330	0.065	275	0.076
F10	–0.064	705	0.031	253	0.085
F27	–0.099	286	0.076	225	0.097

* Measured using a Cu/$CuSO_4$ reference electrode.

All of the corrosion rates were similar and low. This confirms the general indication given by the half-cell potential measurements. The agreement between the corrosion rates estimated using the two techniques was generally good, with all of the estimates within a factor of 2 or 3. In 1997, linear polarization measurements were performed on the eastbound travel lane LMC-III and the westbound passing lane SFC. Tests were made at locations with high, medium, and low corrosion potentials. The testing was performed using a James Instruments GECOR 6 Polarization Resistance Tester. The results of the testing for both the eastbound travel and the westbound passing lanes are shown in table 26. The corrosion rates were moderate and are higher in 1997 than in 1994 LMC. There is no appreciable difference in the corrosion rates between the two types of overlay.

Table 26. Results of polarization resistance testing at U.S. 52 (1997).

Direction	Grid Location	Half-Cell Potential (mV)	Measured Corrosion Rate (μA/cm^2)	Notes
Eastbound Travel LMC	B10	–129	0.137	Low potential, wheel path
	D98	–139	0.135	Low potential, wheel path
	C68	–185	0.160	Centerline
	C108	–183	0.173	Centerline
	B110	–199	0.232	Centerline, cracks
	D34	–264	0.232	-
Westbound Passing SFC	F38	–202	0.160	-
	C60	–133	0.078	Shoulder, not confined
	D38	–315	0.114	Delam in base concrete, not confined
	D102	–97	0.179	Low potential
	H110	–337	0.132	At edge of delam
	H110	–378	0.145	Over delam
	E120	–97	0.175	Centerline
	G180	–139	0.086	Wheelpath

CORE TESTING

Concrete cores were taken through the overlays in 1994 and 1997. They were inspected to determine the overlay thickness and the cover over the uppermost reinforcing bars. The overlay thickness on the eastbound and westbound travel lanes, which are both latex-modified concrete, ranges from 25 to 50 mm (1 to 2 inches). The clear cover above the reinforcing steel ranges from 76 to 102 mm (3 to 4 inches). In 1994, three of the cores removed from the westbound travel lane and three cores removed from the eastbound travel lane were tested to determine their bond strength in direct shear.

The results of the testing are shown in table 27. All of these cores have the latex-modified concrete overlay and there is little difference between the two spans. This is to be expected as both failed primarily in the substrate concrete, which was nominally the same in both locations. The failure of the cores primarily in the substrate concrete indicates that the surface preparation and application was excellent for the latex-modified overlay, as improper installation or poor surface preparation will typically result in failures at the bond line.

In 1997, three cores from the eastbound travel lane LMC-III and three cores from the westbound passing lane SFC were tested in shear. The results are shown in table 28. The bond strengths of the cores from the westbound passing lane SFC are less than that of the cores from the eastbound travel lane LMC, but there is significant scatter among the data. Failures occurred mainly in the substrate concrete. If the test result from the core taken in the shoulder of the eastbound lane or the core taken from the center line of the westbound lane is excluded, there is little difference between the two sections.

Table 27. Shear bond testing of cores from U.S. 52 (1994).

Overlay Type	Core ID	Bond Strength MPa (psi)	Failure Location (percent of failure area)		
			Overlay	Bond Line	Substrate
Eastbound	1	4.1(596)	5	0	95
Travel	2	2.8 (407)	10	0	90
LMC	5	3.6 (517)	10	0	90
Westbound	1	4.9 (716)	0	0	100
Travel	2	4.0 (580)	10	0	90
SFC	3	3.4 (486)	10	0	90

Table 28. Shear bond testing of cores from U.S. 52 (1997).

Location and Overlay Type	Core ID	Exposure Condition	Bond Strength MPa (psi)
Eastbound Travel LMC	3	Wheel path	4.7 (680)
	5	Centerline	5.9 (850)
	7	Shoulder	7.2 (1040)
Average			**5.9 (857)**
Westbound Passing SFC	3	Shoulder	4.9 (710)
	8	Centerline	3.2 (470)
	9	Wheel path	5.0 (720)
Average			**4.4 (633)**

CHLORIDE ANALYSIS

In 1994, following the visual examination of the cores, chloride analyses were performed on six cores from the eastbound travel lane and seven cores from the westbound travel lane. Concrete slices were taken from the 12- to 25-mm (0.5- to 1-inch) depth surface region and from the 95- to 120-mm (3.75- to 4.75-inches) depth where the reinforcing bars are typically located. All of the slices were pulverized and analyzed to determine their acid-soluble chloride content. In addition to the acid-soluble chloride analyses, water-soluble chloride analyses were performed on selected samples. The test results for 1994 are shown in table 29. In 1998, chloride analyses were performed on two cores from the eastbound passing lane LMC, one core from the eastbound travel lane LMC, one core from the westbound travel lane LMC and two cores from the westbound passing lane SFC. The acid-soluble chloride contents were measured at 4 depths up to the 95- to 120-mm (3.75- to 4-inch) depth. The results are shown in table 30.

All of the locations had low to moderate chloride concentrations at the level of the reinforcing bars. The approximate threshold for chloride-induced corrosion of black reinforcing steel is approximately 0.025 percent by concrete weight, so most of the locations in the deck appear to have only marginally sufficient chloride to support corrosion. This agrees with the indication of little corrosion given by the half-cell potential and corrosion rate readings. The relatively high chloride contents at the bond line area (28 to 38 mm (1.125 to 1.5 inches)) indicate that chloride contamination of the surface of the original deck remained when the overlays were placed. Chloride ingress into the overlay concrete has occurred with time both from the surface and from the chlorides that were present in the surface region of the substrate concrete.

Table 29. Results of chloride content testing of cores from U.S. 52 (1994).

Location and Overlay Type	Sample Number	Acid-Soluble Chloride Content, percent by concrete weight		Water-Soluble Chloride Content, percent by concrete weight	
		0.5 to 1 inch	3.75 to 4 inches	0.5 to 1 inch	3.75 to 4 inches
Eastbound Latex Modified	1	-	0.033	-	-
	2	0.011	0.036	-	-
	3	0.027	0.047	0.010	0.017
	4	-	0.018	-	-
	5	0.017	0.018	-	-
	6	-	0.024	-	< 0.007
Westbound Latex Modified	1	-	0.008	-	-
	2	-	0.039	-	-
	4	0.048	0.025	-	-
	5	0.022	0.046	< 0.007	0.018
	6	-	0.017	-	< 0.007
	7	0.025	0.018	-	-

Table 30. Results of chloride content testing of cores from U.S. 52 (1998).

Location and Overlay Type	Acid-Soluble Chloride Content, percent by weight of concrete			
	0.25 to 0.5 inch	0.625 to 1 inch	1.125 to 1.5 inches	3.75 to 4 inches
Eastbound Passing #1 LMC	0.179	0.104	0.151	0.048
Eastbound Passing #2 LMC	0.152	0.139	0.197	0.090
Eastbound Travel LMC	0.109	0.063	0.089	0.022
Westbound Travel LMC	0.067	0.050	0.133	0.035
Westbound Passing #1 SFC	0.119	0.049	0.248	0.052
Westbound Passing #2 SFC	0.091	0.097	0.289	0.053

SUMMARY OF U.S. 52 TEST (NEW RICHMOND, OH)

The SFC and LMC-III overlays were placed in April 1992. Overall, the overlays were in good condition in 1998. Each overlay has developed some delamination but the percent delaminated area is very low and less than 1 percent. Some plastic cracking is present, predominantly in the LMC-III overlays. The bond remains strong in both sections.

Half-cell potential data and corrosion rate measurements indicate a low probability of widespread corrosion. Table 31 shows the percent of potentials more positive than –250 mV, indicating the areas with a low probability of corrosion. The chloride content at the level of the reinforcing in moderately low. Some chloride ingress into the overlays was noted, however, their performance is considered very good.

Table 31. Potentials more positive than –250mV ($Cu/CuSO_4$) (percent of measurements).

Year	NB (SFC)	SB (LMC-III)
1994	-	98.8
1997	96.8	97.3

CHAPTER 5. I–265 OVER KY 22, JEFFERSON COUNTY, KY

INTRODUCTION

This test site consists of two medium-length (42 m, 243 ft) three-span parallel bridges carrying I–265 over KY 22, approximately 11 km (7 miles) northeast of the Louisville city limits on KY 22. The end spans are 15 m (49.5 ft) long, and the center span is 42 m (137 ft). The decks were constructed in 1969, and were rated as "satisfactory" by State forces in 1991. They were described as having a few transverse cracks and isolated spalled areas that had been patched with asphaltic material. During work to maintain the riding surface and replace deteriorated joints, the deck was overlaid with concrete overlays. The northbound lanes shown in figure 17, received a LMC-III overlay and the southbound lanes shown in figure 18, received a SFC overlay.

Northbound Lanes – Materials for the LMC-III mix consisted of: Type III cement; a subangular to rounded natural sand consisting of a mixture of siliceous and calcareous minerals having a specific gravity of 2.60, absorption of 1.40 percent, and fineness modulus of 2.56; and a crushed limestone coarse aggregate having a maximum topsize of 12 mm (0.5 inch) with a specific gravity of 2.71 and an absorption of 0.6 percent. The latex used was DPS Modifier A, a styrene-butadiene latex emulsion.

Southbound Lanes – A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: Force 10,000 silica fume (slurry form); Darex II AEA, an organic-acid salt based air-entraining agent; and WRDA-19, a Type F high-range water reducing admixture. The mixture proportions and plastic concrete characteristics for both overlays, as reported in the C-206 report, are shown in table 32.

Figure 17. Photograph of I–265 northbound lanes with latex-modified overlay.

Figure 18. Photograph showing I–265 southbound lanes with silica fume concrete overlay.

Table 32. I–265 concrete proportions and characteristics.

Material	LMC-III	SFC
Cement (lb/yd^3)	658 (Type III)	658 (Type I)
Fine aggregate (lb/yd^3)	1708	1395
Coarse aggregate (lb/yd^3)	1162	1531
Water (lb/yd^3)	219	240
Latex modifier (gal/yd^3)	24.5	-
Silica fume (lb/yd^3)	-	50
HRWRA (oz/yd^3)	-	105
AEA (oz/yd^3)	-	39
W/C ratio	0.33	0.34
Air content (percent)	5.5	6.5
Slump (inches)	5.0	6.0
Temperature (°F)	79	82
Unit weight (lb/ft^3)	144.0	143.8
Placement date	6/08/92	6/29/92
Weather conditions	Clear	Clear

1 lb/yd3 = .347 kg/m3
1 gal/yd3 = 5 l/m3
1 oz/yd3 = .037 kg/m3
1 inch = 25.4 mm
(oF - 32/1.8) = oC
1 lb/ft3 = 16 kg/m3

The Kentucky Department of Highways (KYDOH) specifications on fresh properties of LMC-III include a range of slump from 100 to 150 mm (4 to 6 inches) and an air content not to exceed 7 percent. Specifications for SFC mixes include a slump range of 100 to 178 mm (4 to 7 inches) and an air content range of 5 to 8 percent. As required by the State specifications, the placements took place at night to prevent the hot conditions typically seen during the daytime of the summer months. The LMC-III overlay was placed on June 8, 1992 using two mobile concrete mixers. The water used to pre-wet the deck was noted in inspector diaries to be "excessive" with some water remaining at the bottom of deeply-excavated areas at the time of placement. The surface was textured with a stiff-broom finish. The surface was covered with wet burlap and polyethylene film immediately following the finishing, although no soaker hoses were used. The curing was removed after 24 hours, and no further curing was applied. The LMC-III overlay was opened to traffic two days after casting.

The concrete for the SFC overlay was placed on June 29, 1992 and was delivered using transit-mix trucks. It was placed smoothly and without problems. The surface was finished in a similar manner to the LMC-III overlay. The curing was also similar to that of the LMC-III overlay, except that the wet burlap and polyethylene was maintained on the concrete for 72 hours. Although soaker hoses were not used at the site, the burlap was wetted at the start of each day of curing. The SFC overlay was opened to traffic 13 days after casting.

The northbound and southbound structures are not identical. The northbound structure LMC-III is wider, carrying a merge area across the bridge. Due to the extreme difficulty in closing the northbound travel lane through the merge area, the test section was set up in the shoulder and merge area, and it does not receive “main line” traffic exposure.

VISUAL INSPECTION

The underside of the structure was inspected annually while the traffic control was being set up on the lanes above. The southbound SFC span sits on only seven simple-span girders, and it does not carry a merge lane. The girders were noted to be somewhat rusty and the underside of the bridge exhibited occasional transverse cracks, some with efflorescence. The joints on the edges of the structure exhibited cracking and delamination with exposed bars. The bearing blocks under the rocker bearings were cracked and spalled.

The deck of the structure was inspected visually for appearance and performance. In 1994, the southbound SFC deck had several areas of concentrated "spidery" cracks, with Span 1 appearing worse than the other spans. The cracks were a mix of longitudinal and transverse cracks, and were concentrated primarily in the travel lane. In 1998, the cracking had become more noticeable and was generally more severe in the travel lane than the shoulder. Span 1 had the most severe cracking with some located in the shoulder as well as the travel lane. In all three spans, the cracking is more severe in the wheel paths. Most of the cracking is longitudinal with some shorter transverse cracking. The crack widths of the major cracks range from 0.127 to 0.381 mm (0.005 to 0.015 inches).

The northbound structure LMC is wider than the southbound structure, carrying a merge area across the bridge. Because of the merge area, the northbound traffic on the south side of the bridge was brought into one lane, into which the on-ramp traffic was merged. Because of these traffic control requirements, the test section was set up in the shoulder and merge area, and does not receive “main line” traffic exposure. The initial inspection in 1994 showed narrow cracks, many of which had healed by 1998. Cores showed cracks about 6 mm (0.25 inch) deep. The inspection in 1998 showed the overlay to be in good condition. There were several rough surface areas both in the shoulder and the merge lane but very little cracking. There were occasional short transverse and longitudinal cracks but no major cracks. The condition of the latex modified concrete overlay is much better than the silica fume concrete overlay but this is partly because the latex-modified overlay test section is subjected to a lesser amount of traffic.

DELAMINATION SURVEY

The chain drag and hammer survey techniques were used to locate and delineate areas of delamination of the overlay concrete from the old concrete deck. Delaminations were found mostly at crack locations. The number and total area of delaminations on the I–265 bridge are shown in tables 33 and 34. The southbound SFC spans have many more delaminations, both in number and area, than the northbound LMC spans.

Table 33. Number and areas of delaminations, southbound I–265 SFC.

Year	No. Areas	Total Area (m^2)	Percent of Total Area
1994	0	0.00	0.00
1995	11	1.48	0.33
1996	25	7.75	1.71
1997	45	13.33	2.95
1998	60	20.20	4.47

Table 34. Number and areas of delaminations, northbound I–265 LMC.

Year	No. Areas	Total Area (m^2)	Percent of Total Area
1994	0	0.00	0.00
1995	2	0.18	0.05
1996	6	0.97	0.25
1997	13	1.62	0.42
1998	17	3.46	0.90

Of the southbound spans, the first span on the approach end of the bridge has the most severe delaminations of the three spans. Also, most of the delaminations are located in the travel lane and not in the shoulder areas. For the northbound structure, almost all of the delaminations are located in the center span. The areas of the two test sections are different because the northbound section tapers at the end where the merge lane ends. The area of the southbound SFC section is 452 m^2 (4,860 ft^2) and the area of the northbound section LMC is 384 m^2 (4,130 ft^2). Tables 33 and 34 show the percentage of the total area delaminated is 4.47 percent for the southbound sections SFC and 0.90 percent for the northbound LMC section. The southbound section appears much worse than the northbound but still has moderately little delaminated area and also has much more traffic than the northbound section.

HALF-CELL POTENTIAL SURVEY

The potential survey test grid on the southbound SFC bridge was marked using a 0.6-m (2-ft) grid beginning at the approach end of each span. Each span was numbered independently. The transverse rows were numbered from 1 to 25 and 1 to 68 from the approach side to the leave side, for the end and center spans, respectively. The longitudinal rows were lettered A to K, with the A-line placed along the paint stripe separating the travel lane from the passing lane. In the survey from 1994, the half-cell potential readings ranged from approximately +50 mV to –414 mV, with large potential differences between nearby areas. These readings tend to indicate that some limited corrosion is taking place in the bridge. Span 1 appeared to have the most corrosion activity, with rapid potential changes noticeable between nearby areas and an average potential reading of –211 mV. Span 2 had the highest (most negative) potential reading but also the lowest average potential reading of –136 mV. Span 3 had an average potential reading of –191 mV.

In 1997, the half-cell potentials ranged from +265 mV to –600 mV. Span 1 again had the highest average potential reading of –207 mV. Span 2 again had the highest potential reading at –600 mV and the lowest average reading at –149 mV. Span 3 had an average potential reading of –160 mV. Tables 35 and 36 give the cumulative frequencies of the half-cell potentials for the southbound test section of I–265 for 1994 and 1997, respectively. In 1994, over 85 percent of the readings were less negative than –250 mV. In 1997, over 86 percent of the readings were less negative than –250 mV. A histogram of the half-cell potential readings for the southbound test section in 1994 and 1997 is shown in figure 19.

Table 35. Cumulative frequency of half-cell potentials for I–265 for SB travel lane, SFC (1994).

Potential Range **(mV)**	**Number of Observations**	Cumulative Percentage
0 to –49*	54	4.1
–50 to –99	259	23.5
–100 to –149	312	46.9
–150 to –199	272	67.3
–200 to –249	244	85.6
–250 to –299	128	95.2
–300 to –349	50	99.0
–350 to –399	10	99.8
–400 to –449	2	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

*Note. Any positive reading is counted as 0 for tabulation.

Table 36. Cumulative frequency of half-cell potentials for I–265 for SB travel lane, SFC (1997).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to –49*	53	4.0
–50 to –99	215	20.1
–100 to –149	355	46.6
–150 to –199	323	70.7
–200 to –249	212	86.5
–250 to –299	113	94.9
–300 to –349	48	98.5
–350 to –399	17	99.8
–400 to –449	1	99.9
–450 to –499	1	100.0
–500 to –549	0	100.0

*Note. Any positive reading is counted as 0 for tabulation.

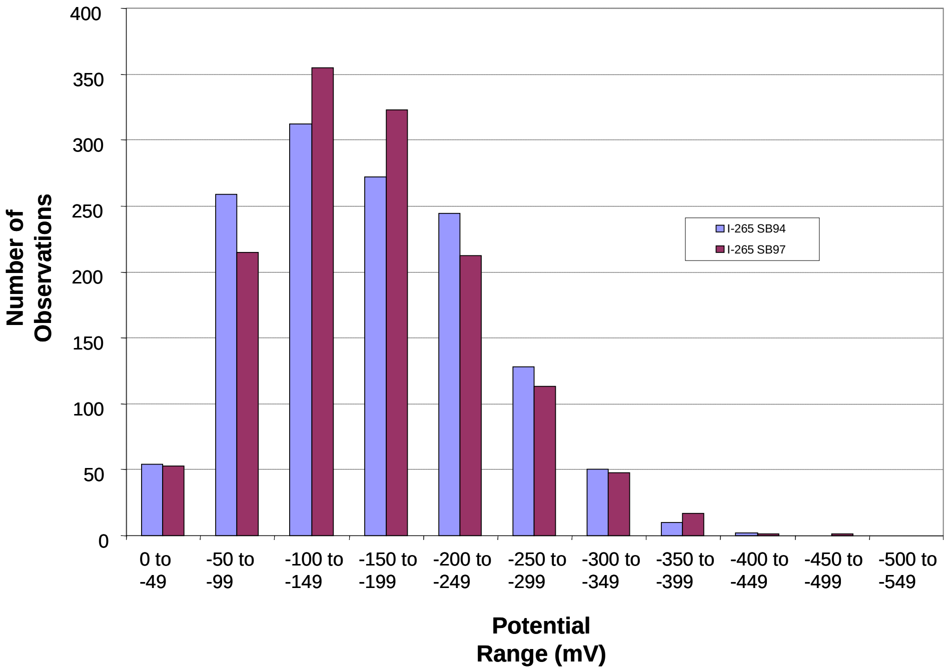


Figure 19. Histogram of half-cell potential readings for I–265 southbound SFC test section.

The 0.6-m (2-ft) grid for the northbound LMC spans was started at the approach side of the bridges. The transverse rows of points were numbered from 1 to 25 and 1 to 69 on the end and center spans, respectively. The longitudinal were lettered A to K, beginning at the paint stripe between the travel and passing lanes. Due to tapering of the merge lane across the bridge, row H was the last row at the leave end of the bridge. The half-cell potential for the northbound test section in 1994 readings ranged from +59 mV to −356 mV, with the more negative potentials occurring primarily at the joints. In 1994, span 3 had the highest average potential reading at −102 mV.

Span 2 had the highest individual reading at –356 mV but had an average reading of only –65 mV. Span 1 had an average potential reading of –55 mV. In 1997, span 3 again had the highest average potential reading at −86 mV but also had the highest individual reading at −352 mV. Span 2 had an average potential reading of −61 mV and span 1 had an average of −27 mV. Tables 37 and 38 show the cumulative frequency of the half-cell readings for the northbound spans in 1994 and 1997. A histogram of the half-cell potential readings for the northbound test section for 1994 and 1997 is shown in figure 20. In 1994 and 1997, approximately 98 percent of the readings were less negative than −250 mV. In areas away from the joints, the potentials were generally less negative than −100 mV, indicating that very little corrosion is taking place in the bridge.

Figure 21 shows an equipotential map of the half-cell readings for the southbound SFC test section for 1997. Spans 1 and 3 appear to have more isolated spots of corrosion (anodic) activity than the main span. An equipotential map of the half-cell potential readings for the northbound LMC test section for 1997 is shown in figure 22. The magnitude of the half-cell readings is much lower in the northbound LMC test section than in the southbound SFC test section. However, some anodic areas are present, mainly near the joints and in the main span.

Table 37 Cumulative frequency of half-cell potentials for I–265 for NB travel lane, LMC (1994).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to −49	494	46.1
−50 to −99	317	75.7
−100 to −149	134	88.2
−150 to −199	74	95.1
−200 to −249	33	98.2
−250 to −299	15	99.5
−300 to −349	4	99.9
−350 to −399	1	100.0
−400 to −449	0	100.0
−450 to −499	0	100.0
−500 to −549	0	100.0

Table 38. Cumulative frequency of half-cell potentials for I–265 for NB travel lane, LMC (1997).

Potential Range (mV)	Number of Observations	Cumulative Percentage
0 to −49	626	60.0
−50 to −99	226	81.6
−100 to −149	98	91.0
−150 to −199	45	95.3
−200 to −249	32	98.4
−250 to −299	14	99.7
−300 to –349	2	99.9
–350 to –399	1	100.0
–400 to –449	0	100.0
–450 to –499	0	100.0
–500 to –549	0	100.0

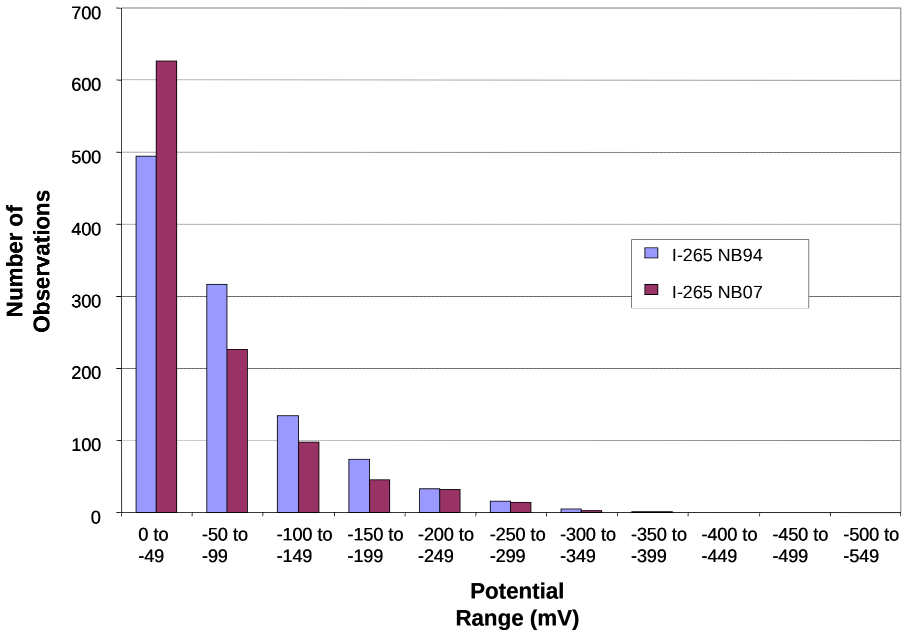
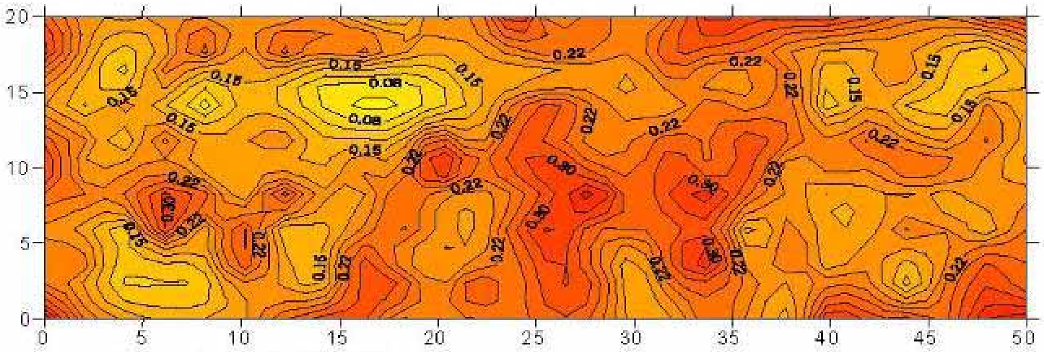
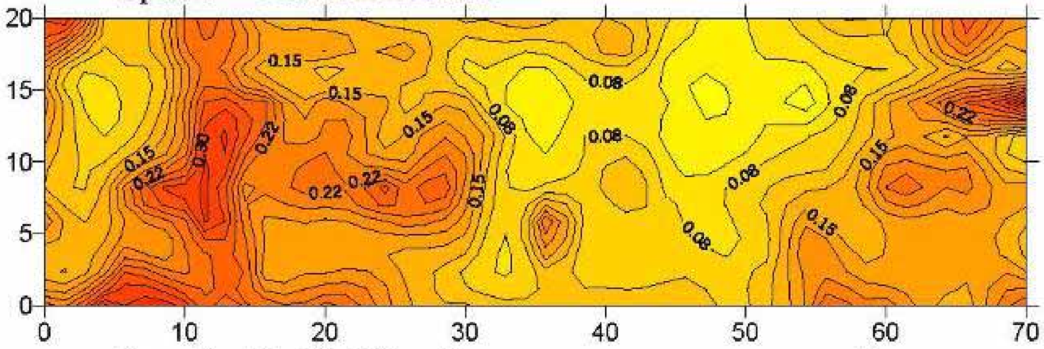


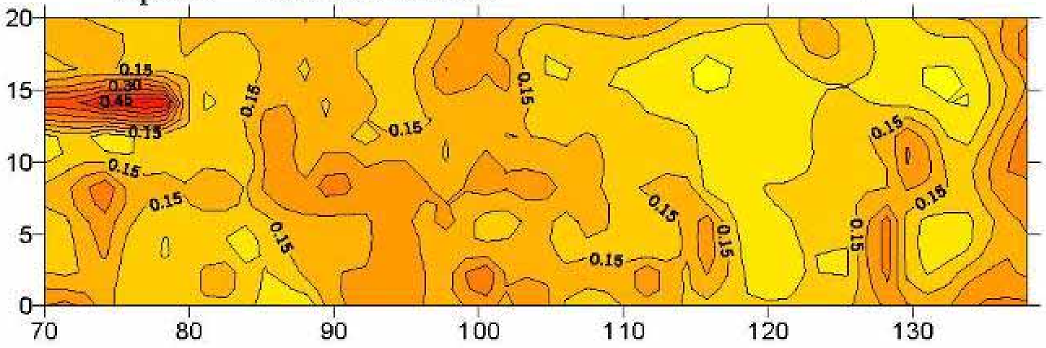
Figure 20. Histogram of half-cell potential readings for the I–265 northbound LMC test section.



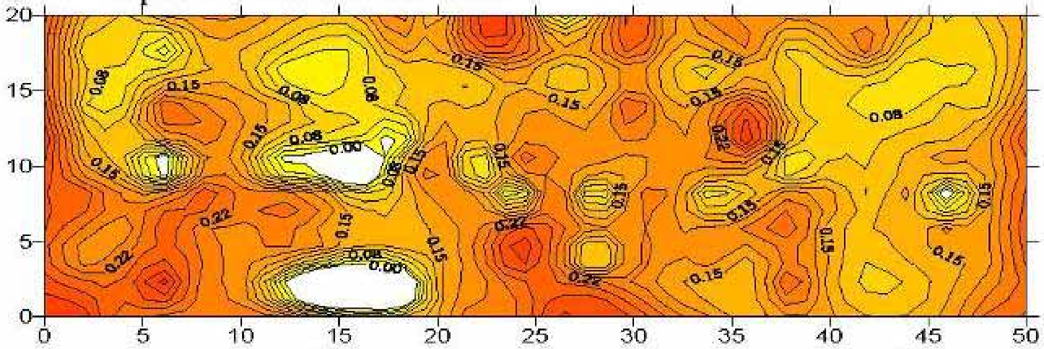
Span 1—Traffic Direction



Span 2—Traffic Direction



Span 2—Traffic Direction



Span 3—Traffic Direction

Figure 21. Equipotential maps of half-cell potentials of the three southbound spans SFC of the I–265 test section in 1997.

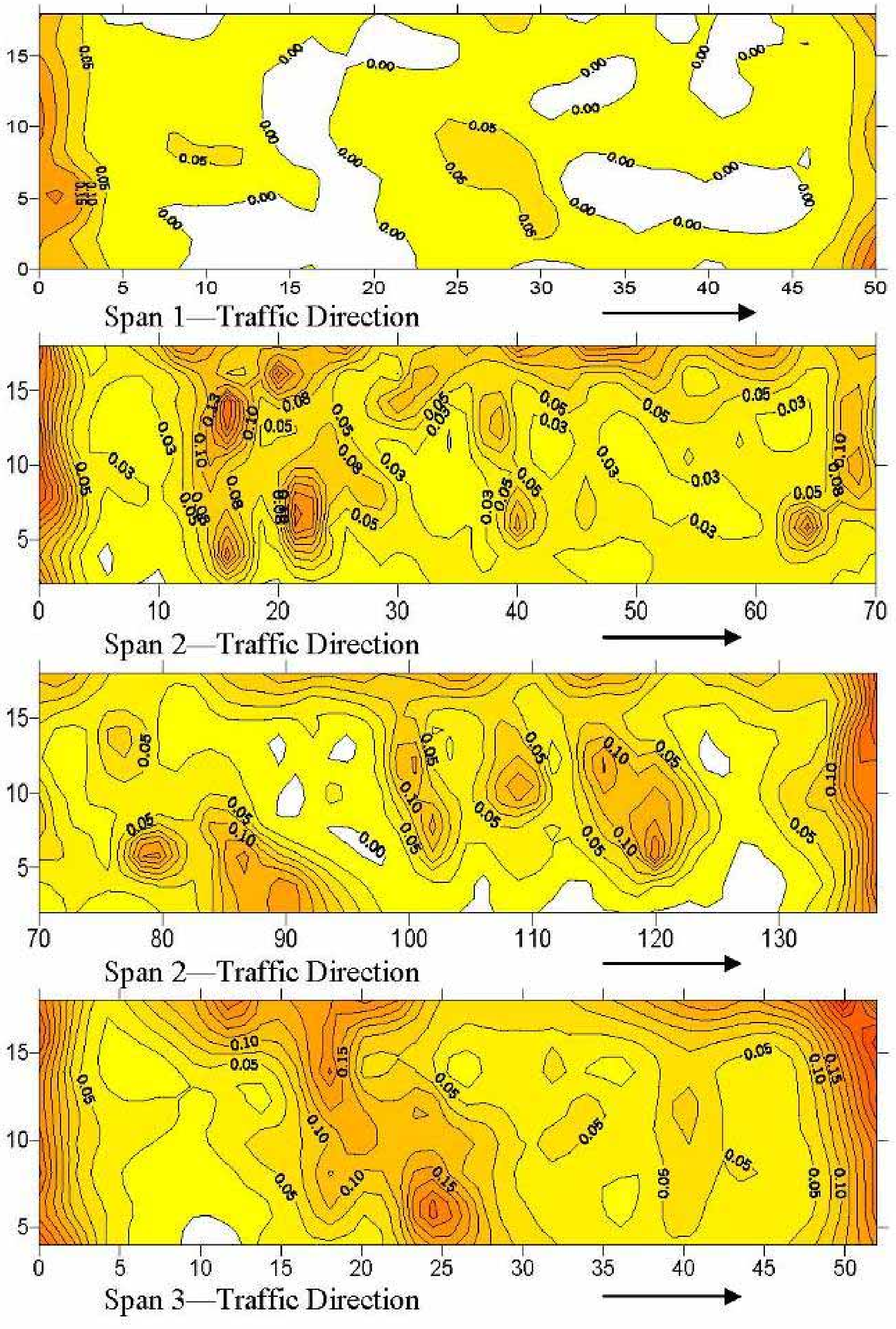


Figure 22. Equipotential maps of half-cell potentials of the three northbound spans LMC of the I–265 test section in 1997.

POLARIZATION RESISTANCE (PR) TESTING

Polarization resistance tests were performed at five locations on the southbound SFC bridge in 1994. The test locations were chosen from low, moderate and high-potential areas. The PR tests were performed using a EG&G Princeton Applied Research Company (EG&G PARC) model 273A potentiostat under computer control. Simulated 3LP tests were also performed at each of the test locations. Only three of the five locations were successfully tested using the PR or the 3LP technique. The results of the testing are summarized in table 39.

Table 39. Corrosion rate testing on I–265 southbound in 1994 SFC.

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
Span 1, I8	–0.259	-	-	565	0.048
Span 1, I28	–0.231	254	0.085	-	-
Span 2, G21	–0.103	390	0.055	195	0.111
Span 3, F10	–0.199	-	-	76	0.286
Span 3, E18	–0.305	696	0.031	-	-

* Measured using a Cu/CuSO$_4$ reference electrode

The corrosion rate measurements were variable and did not generally agree with the half-cell potential measurements, as some of the most negative potentials were associated with the lowest corrosion rates. The 3LP measurements indicated higher corrosion rates than the PR tests. The difficulties encountered may have been related to the high resistivity of the silica fume overlay concrete.

The PR and 3LP testing was only slightly more successful on the northbound LMC structure than on the southbound structure, with four of the six locations being successfully tested using either technique. This may have been due to the overall low corrosion rates observed on the structure, as very low corrosion rates are typically more difficult to measure than actively corroding areas. The results of the testing are summarized in table 40.

Table 40. Corrosion rate testing on I–265 northbound in 1994 LMC.

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
Span 1, C0	–0.151	701	0.030	2400	0.009
Span 1, EF4	–0.119	325	0.067	-	-
Span 1, D16	–0.000	-	-	-	-
Span 3, C18	–0.163	-	-	281	0.077
Span 3, C50	–0.147	11300	0.002	1283	0.016
Span 3, C47	–0.122	8802	0.002	5021	0.004

* Measured using a Cu/CuSO$_4$ reference electrode

In 1997, linear polarization measurements were performed on both spans at locations with high, medium, and low corrosion potentials. Because the southbound SFC structure appeared to have more corrosion activity occurring, the corrosion rate was measured at eight locations while only one location was measured on the northbound structure. The one location on the northbound test section was chosen because it was one of the few areas that had a higher negative potential. The testing was performed using a James Instruments GECOR 6 Polarization Resistance Tester and the results are shown in table 41. There is some scatter in the corrosion rate measurements. The corrosion rates vary from very low to moderately low. Some corrosion appears to be occurring in local areas but at low to moderate rates.

Table 41. Results of polarization resistance testing at U.S. 52 (1997).

Direction	Grid Location	Half-Cell Potential (mV)	Measured Corrosion Rate ($\mu A/cm^2$)	Notes
Southbound Travel SFC	E62	–171	0.093	Random half-cell
	EF34	–212	0.104	Wheelpath
	EF31	–329	0.157	Moderate potential
	H20	–211	0.154	Moderate potential
	C20	–124	0.054	Low potential
	H12	–334	0.061	Negative potential
	E90	–245	0.110	Moderate potential
	EF130	–243	0.114	Delamination area
LMC (NB)	F22	–282	0.212	Delaminated area

CORE TESTING

Cores were taken from both test sections in 1994 and 1997. In the laboratory, the cores were examined to determine the overlay thickness and the cover over the uppermost reinforcing bars. The overlay thicknesses ranged from 32 to 50 mm (1.25 to 2.0 inches) and the observed clear cover over the reinforcing bars ranged from 64 to 95 mm (2.5 to 3.75 inches). In 1994, shear bond testing was performed on three cores from each test section. The test results are shown in table 42. The test result for one of the cores from the northbound test section was much higher than all the others. This is because the failure occurred completely in the overlay. Without this result, there is no appreciable difference in the bond strength of the cores from either test section. All the other cores failed mostly or completely in the base concrete.

Table 42. Shear bond testing of cores from I–265 (1994).

Overlay Type	Core ID	Bond Strength MPa (psi)	Failure Location (percent of failure area)		
			Overlay	Bond Line	Substrate
Southbound	1	3.4 (493)	25	0	75
Travel	4	3.9 (570)	30	0	70
SFC	8	2.9 (420)	40	20	40
Northbound	1	5.7 (827)	100	0	0
Travel	2	2.9 (424)	10	0	90
LMC	3	4.0 (580)	0	0	100

In 1997, four cores from the southbound travel lane and one core from the northbound travel lane were tested in shear. The results are shown in table 43. The bond strength of all the cores remains good and most failures occurred in the substrate or overlay concrete.

Table 43. Shear bond testing of cores from I–265 (1997).

Location and Overlay Type	Core ID	Exposure Condition	Bond Strength MPa (psi)
Southbound Travel LMC	4	Shoulder	3.7 (540)
	5	Centerline	3.9 (570)
	6	Centerline	4.4 (640)
	7	Wheel path	3.9 (560)
Average			4.0 (578)
Northbound Travel SFC	4	Wheel path	3.2 (460)

CHLORIDE ANALYSES

Following the visual examination of the cores, chloride analyses were performed on six cores from each overlay taken in 1994. The samples were taken from the 25- to 50-mm (0.5- to 1-inch) depth surface region and from the 75- to 95-mm (3- to 3.75-inches) depth where the reinforcing bars would have been located. All of the slices were then pulverized and analyzed to determine their acid-soluble chloride content. In addition to the acid-soluble chloride analyses, water-soluble chloride analyses were performed on selected samples. The results of the testing are shown in table 44.

Table 44. Results of chloride content testing of cores from I–265 (1994).

Overlay Type	Sample Number	Acid-Soluble Chloride Content, percent by concrete weight		Water-Soluble Chloride Content, percent by concrete weight	
		0.5 to 1 inch	3 to 3.75 inches	0.5 to 1 inch	3 to 3.75 inches
Southbound Travel SFC	S 2A	0.031	0.117	0.015	0.065
	S 5	< 0.007	0.018	-	-
	S 6	-	< 0.007	-	-
	S 7	0.010	0.095	-	-
	S 9	-	0.040	-	-
	S GRND	-	0.065	-	-
Northbound Travel LMC-III	N 1	-	0.027	-	-
	N 5	0.019	0.034	0.011	0.017
	N 7	0.039	0.034	0.018	0.018
	N 8	0.010	0.080	-	-
	N GRND 3	0.016	-	-	-
	N X	-	0.039	-	-

All of the locations had moderate to low chloride concentrations at the level of the reinforcing bars. The water-soluble chlorides were considerably lower than the acid-soluble results. The approximate threshold for chloride-induced corrosion of black reinforcing steel is approximately 0.025 percent by concrete weight, so only some of the locations in the deck appear to have sufficient chloride to support corrosion. In 1998, one core from each test section was analyzed for chloride. The chloride was measured at four depths as shown in table 45.

Table 45. Results of chloride content testing of cores from I–265 (1998).

Location and Type Overlay	Acid-Soluble Chloride Content, percent by weight of concrete			
	0.25 to 0.5 inch	0.625 to 1 inch	1.125 to 1.5 inches	3.75 to 4 inches
Southbound Travel SFC	0.110	0.045	0.100	0.021
Northbound Travel LMC	0.077	0.047	0.151	0.076

The chloride levels at the reinforcing bars are similar to those in 1994. Some chloride has penetrated into the near surface of the overlays and to a depth of 25 to 50 mm (0.5 to 1 inch). Elevated chloride levels are present at the 28 to 38 mm (1.125 to 1.5 inches) level likely due to chloride contamination in the original deck surface.

SUMMARY OF I–265 OVER KY 22 (JEFFERSON COUNTY, KY)

The SFC and LMC-III overlays were placed in June 1992. The SFC test section carries main line traffic while the LMC-III test section carries a shoulder and merge lane. The SFC overlay has developed progressive cracking with cracking being most severe in the wheelpaths. Delaminations have increased with time and 4.5 percent of the overlay was delaminated in 1998. The LMC-III overlay test area has much less cracking and few delaminations, 0.9 percent in 1998, however, it does not handle main line traffic.

The half-cell potential data had values more positive than –250 mV (noncorrosive) for 86 percent of the measurements on the SFC overlay and 98 percent of the measurements on the LMC overlay. These percentages did not change between 1994 and 1997. Local anodic locations were present for both overlays. The corrosion rates tended to be low with some areas being moderate to low. The bond of the overlays, away from delaminations, remained high over the test period. Chloride has penetrated into the surface of the overlays and some chloride was present in the near surface of the existing substrate concrete. The chloride content at the level of the reinforcing steel remains low to moderately low.

CHAPTER 6. U.S. 41 OVER KY 351, HENDERSON, KY

INTRODUCTION

This test site consists of twin three-span (48 m (159 ft)) parallel bridges located on U.S. 41 over Kentucky State Highway at milepost 12 on the Henderson City bypass route. The three spans are each 16 m (53 ft) long. The spans are of composite deck/girder construction. The bridges were constructed in 1959, and a low-slump concrete overlay was placed on the decks in the mid-1970's. In 1992, an inspection by State forces indicated that the overlays were mapcracked and exhibiting considerable wear. The deck had also been patched numerous times and the patches were noted to be deteriorating. Because of the deck condition, the bridges were scheduled for overlay. A LMC-III overlay was applied to the northbound lanes, figure 23, and a SFC overlay was applied to the southbound lanes, figure 24.

Figure 23. Photograph of northbound test section of U.S. 41 (latex-modified concrete overlay).

Figure 24. Photograph of southbound test section of U.S. 41 (silica fume concrete overlay).

The concrete materials and proportions, as reported in the C-206 report, are as follows: materials selected for the LMC-III mix consisted of a Type III cement; an angular to rounded siliceous natural sand having specific gravity of 2.61 and an absorption of 1.00 percent; and a crushed limestone coarse aggregate having a maximum top size of 12 mm (0.5 inch) with a specific gravity of 2.71 and an absorption of 0.7 percent. The latex used was DPS Modifier A, a styrene-butadiene latex emulsion.

A Type I cement was used in the SFC mix. Aggregates were from the same sources used for the LMC-III mix at this site. Admixtures included: (1) MB-SF silica fume (compacted powder form); (2) Micro-Air, a synthetic air-entraining agent; and (3) Rheobuild-1000, a Type F high-range water reducing admixture. The mixture proportions and plastic concrete characteristics, as reported in the C-206 report, are shown in table 46.

Table 46. U.S. 41 over KY 351 concrete proportions and characteristics.

Material	LMC-III	SFC
Cement (lb/yd^3)	658 (Type III)	658 (Type I)
Fine Aggregate (lb/yd^3)	1610	1366
Coarse Aggregate (lb/yd^3)	1260	1536
Water (lb/yd^3)	260	236
Latex Modifier (gal/yd^3)	24.5	-
Silica Fume (lb/yd^3)	-	50
HRWRA (oz/yd^3)	-	98
AEA (oz/yd^3)	-	8
W/C ratio	0.39	0.33
Air content (percent)	6.0	5.6
Slump (inches)	6.5	3.8
Temperature (^{o}F)	77	75
Unit Weight (lb/ft^3)	138.0	140.8
Placement Date	8/13/92	7/8/92
Placement Time	19:35	21:15
Weather Conditions	Clear	Clear

1 lb/yd^3 = .347 kg/m^{3}1
1 inch = 25.4 mm
1 gal/yd^3 = 5 l/m^3
1 oz/yd^3 = .037 kg/m^3
(^{o}F - 32/1.8) = ^{o}C
1 lb/ft^3 = 16 kg/m^3

The SFC was placed on the southbound structure on the night of July 8, 1992. The night placement was in compliance with State specifications. The SFC concrete was delivered in transit-mix trucks. The bonding grout was noted to be applied unevenly, and in some cases the mortar was brushed out of the concrete in lieu of a grout. Mr. Robbie Hecker of the Kentucky Transportation Cabinet told the contractor that on the first span, the bonding grout was spread too far ahead of the paver during placement. This resulted in its possible drying before the overlay concrete was placed. The placement of the second span proceeded normally. The concrete placed on the third span had a high slump of 190 to 200 mm (7.5 to 8.0 inches). This resulted in possible segregation, bleeding, and finishing problems with the concrete. After the overlay was placed, the surface was textured with a stiff-broom finish. The concrete was cured by covering with wet burlap and polyethylene immediately following the finishing operation. Soaker hoses were used to maintain the deck in a saturated condition for the full 72-hour curing period. The SFC overlay was opened to traffic on July 20, 1992, 12 days after casting.

The LMC-III overlay was not placed on the northbound structure until August 13, 1992. The concrete was delivered using mobile concrete mixers. Similarly to the SFC overlay site, there was a nonuniform application of the bonding grout brushed out of the concrete. The surface was finished in the same manner as the SFC deck. The curing was also the same as for the SFC overlay, except that the moist curing was carried out for only 24 hours. The section was opened to traffic on August 18, five days after placement.

VISUAL INSPECTION

The underside of the two bridges was inspected each year while the traffic control was being set up. The underside of the deck was in good condition except for rust, spalls, and leakage at the joints. The substructure was showing signs of deterioration, especially at the bent caps. The bent caps were cracked, spalled, and corrosion stained. Many of the cracks were part of full map patterns with associated efflorescence. Horizontal cracks were also noted in the pier caps. The bearing blocks in the abutments were cracked and spalled.

Horizontal cracks in the bridge beams were seen in the exterior beams of both bridges near the abutments. The structures have six integrally cast concrete beams, with joints between the three simple spans. The beams do not sit on bearing pads, instead tie to integral diaphragms that are keyed into the pier caps. The piers of both structures were in moderate to poor condition, with large cracks, spalls, corrosion products, and efflorescence stains present. Some horizontal cracking, staining, and efflorescence was seen in the south abutment of the northbound structure.

The underside of the deck of the northbound structure was mainly crack-free although some fine transverse cracking could be seen on the underside of the deck near the southern abutment where closer examination was possible. The underside of the deck of the southbound structure was in similar condition.

Inspection of the deck surface of the northbound LMC structure indicated the performance of the three spans was quite different, with Spans 1 and 3 exhibiting heavy transverse and longitudinal cracking and Span 2 exhibiting hardly any cracking. Figure 25 shows typical cracking on the northbound deck. Over the last two years of the study the cracking became worse. Several cracks had lengthened or were becoming interconnected with other cracks. The surface of all three spans in the driving lane was heavily abraded compared to that of the passing lane.

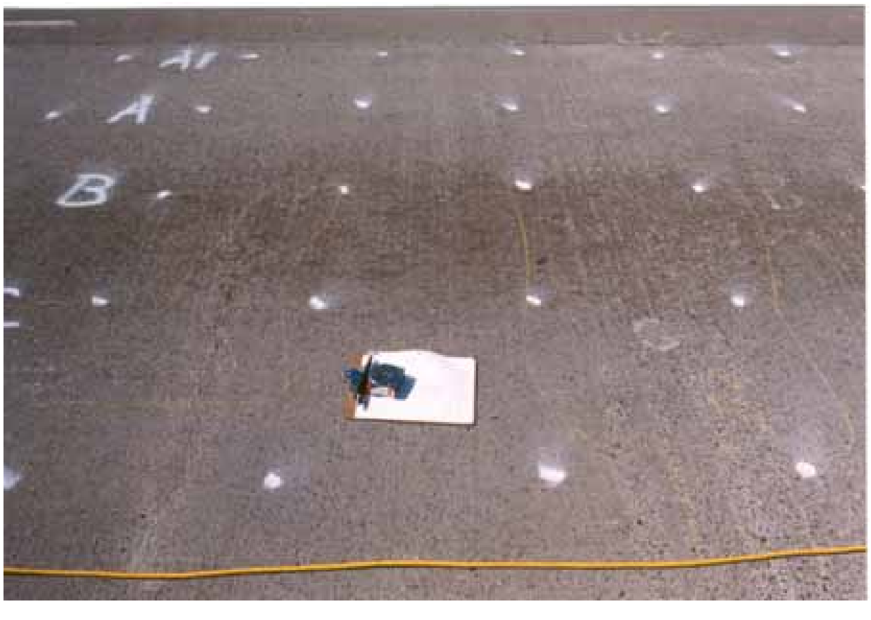


Figure 25. Photograph showing typical cracking found in the northbound deck of the U.S. 41 test section LMC.

Inspection of the deck of the southbound SFC structure revealed the three spans also performing differently. Span 1 was different than Spans 2 and 3 due to its many large and raveled cracks. Many of the cracks increased in length or joined nearby cracks over the five years of the study. In Spans 2 and 3, many of the newer cracks were longitudinal but a few transverse cracks also developed. Span 3 was more heavily cracked than Span 2. In the last year of the study, many of the cracks in the two spans that earlier were only visible after a rainstorm, were now plainly visible when the deck was dry. Figure 26 shows some typical cracking associated with the southbound test section.

DELAMINATION SURVEY

The delamination surveys were performed using a chain drag. The integrally cast beams made defining the edges of the delaminated areas difficult as the sound of the chains varied over the beams. Hammer tapping with a dry sand was also used to define the edges of the delaminated areas. The results of the delamination survey for all 5 years are shown in tables 47 and 48. The number and area of delaminations in each span is given because there are considerable differences between the different spans of each test section.

The southbound test section SFC is performing well. No delaminations were found in any of the spans in 1994 or 1995 and the center span had no delaminations found in any year of the study. The total delaminated area of all three areas is 6.59 m^2 (71 ft^2), 3.72 percent of the total area. The northbound LMC test section performed much worse than the southbound SFC section. All three spans of the northbound structure had delaminations in the first year of the study (1994). The center span is performing the best with only 4.46 m^2 (48 ft^2) square meters or 7.55 percent of the area delaminated. The two end spans are performing much worse with 16.40 m^2 (176 ft^2) (27.8 percent) and 11.47 m^2 (123 ft^2) (19.4 percent) of the surface area delaminated.

Figure 26. Photograph showing typical cracking associated with the southbound test section of U.S. 41 SFC.

Table 47. Number and area of delaminations (U.S. 41 southbound SFC).

Year	Span Number	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	All	0	0.00	0.00
1995	All	0	0.00	0.00
1996	1	7	0.70	1.18
	2	0	0.00	0.00
	3	2	0.14	0.24
	Total	**9**	**0.84**	**0.47**
1997	1	18	1.67	2.82
	2	0	0.00	0.00
	3	8	0.60	1.02
	Total	**26**	**2.27**	**1.28**
1998	1	30	4.92	8.32
	2	0	0.00	0.00
	3	9	1.67	2.82
	Total	**39**	**6.59**	**3.72**

Table 48. Number and area of delaminations (U.S. 41 northbound LMC).

Year	Span Number	Number of Areas	Total Area (m^2)	Percent of Total Area
1994	1	2	0.37	0.63
	2	1	0.18	0.30
	3	3	1.02	1.72
	Total	**6**	**1.57**	**0.88**
1995	1	14	2.60	4.40
	2	5	0.46	0.78
	3	19	2.50	4.23
	Total	**38**	**5.56**	**3.14**
1996	1	21	4.78	8.09
	2	8	0.88	1.49
	3	28	3.90	6.60
	Total	**57**	**9.56**	**5.39**
1997	1	27	10.36	17.53
	2	11	1.53	2.59
	3	31	5.57	9.42
	Total	**69**	**17.46**	**9.85**
1998	1	19	16.40	27.75
	2	14	4.46	7.55
	3	32	11.47	19.41
	Total	**65**	**32.33**	**18.24**

The number of delaminations increased each year on the southbound structure from 0 in 1994 to 39 in 1998. On the northbound structure, the number of delaminations increased from 6 in 1994 to 69 in 1997 then decreased to 65 in 1998. This decrease was because several delaminated areas merged together to form larger delaminations.

HALF-CELL POTENTIAL SURVEY

A 0.6-m (2-ft) grid was marked out beginning at the approach end of the bridges. The longitudinal rows of points were numbered from 1 to 26 from the approach side to the leave side. The transverse rows were lettered A to F, beginning approximately at the paint stripe separating the travel lane from the passing lane. Each span was numbered independently. The half-cell potentials were measured at every point of the 0.6 m (2 ft) grid spacing over both entire bridges.

A summary of the half-cell potential measurements for the southbound travel lane SFC of the U.S. 41 test section in 1994 is shown in table 49. Span 1 had the most negative (corrosive) half-cell potentials of the three spans. The most negative measurement was –389 mV and the least negative was –71 mV. The average half-cell measurement for Span 1 was –201 mV compared to –28 mV for Span 2 and –84 mV for Span 3. Span 2 had 54 half-cell readings out of 189 that were positive. The most positive reading was +74 mV. For tabulation, the positive half-cell measurements were classified as 0 mV. Overall, the southbound SFC test section was in good condition in 1994. For Span 1, 76 percent of the half-cell readings were less negative than –250 mV. This compares to 100 percent for Span 2 and 98.4 percent for Span 3. Overall, 91 percent of the measurements were less negative than –250 mV. A histogram of the distribution of half-cell measurements for the three spans in 1994 is shown in figure 27. Span 1 has clearly shifted more negative (corrosive) compared to the other two spans.

Table 49. Cumulative frequency of half-cell potentials for U.S. 41, SFC (SB travel lane 1994).

Potential Range (mV)	Number of Observations				Cumulative Percentage
	Span 1	Span 2	Span 3	Total	
0 to –49*	0	140	53	193	34.0
–50 to –99	9	39	81	129	56.8
–100 to –149	32	5	35	72	61.6
–150 to –199	67	4	13	84	84.3
–200 to –249	35	1	4	40	91.4
–250 to –299	27	0	3	30	96.6
–300 to –349	15	0	0	15	99.3
–350 to –399	4	0	0	4	100.0
–400 to –449	0	0	0	0	100.0
–450 to –499	0	0	0	0	100.0
–500 to –549	0	0	0	0	100.0
–550 to –599	0	0	0	0	100.0
–600 to –649	0	0	0	0	100.0
–650 to –699	0	0	0	0	100.0

* Note. Any positive reading is counted as 0 for tabulation.

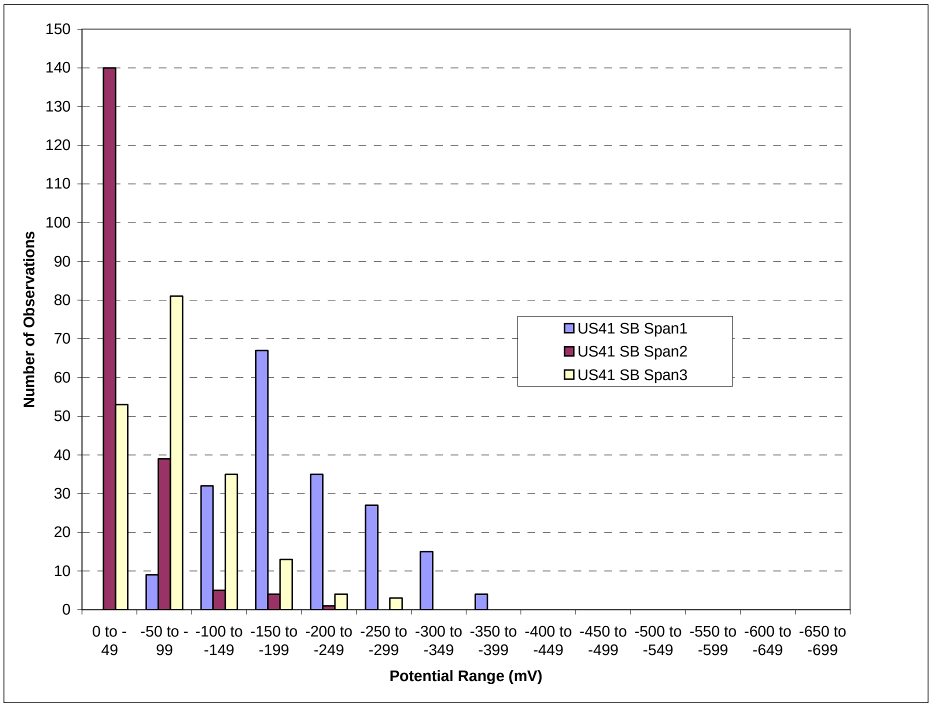


Figure 27. Histogram of half-cell potential readings for U.S. 41 southbound in 1994 SFC.

A summary of the half-cell measurements for the southbound structure in 1997 is shown in table 50. The half-cell measurements were more negative for all three spans in 1997 than in 1994. Span 1 had an average reading of 258 mV with a maximum negative reading of −435 mV and a minimum negative reading of −134 mV. Span 2 had an average of −108 mV with a maximum of −305 mV and a minimum of −19 mV. Span 3 had an average reading of −142 mV with a maximum of −383 mV and a minimum of −16 mV. The average half-cell reading for Span 1 was above the 250 mV threshold for corrosion to occur. A histogram comparing the distribution of half-cell readings for the southbound section in 1997 is shown in figure 28. A histogram comparing the distribution of half-cell measurements for the entire southbound test section in 1994 and 1997 is shown in figure 29. The curve for 1997 is shifted significantly to the right which indicates a probability of increased corrosion activity, especially in Span 1.

A summary of the half-cell potential readings for the northbound LMC spans in 1994 is shown in table 51. Span 3 has higher magnitude half-cell readings than the other two spans. The average half-cell potential reading for Span 3 was −281 mV, compared to −235 mV for Span 1, and −171 mV for Span 2. The average for Span 3 was over the threshold limit of 250 mV needed for corrosion. The maximum half-cell potential for Span 3 is −499 mV, for Span 1 is −425 mV, and for Span 2 is −320 mV. All three spans had half-cell potentials indicative of corrosion occurring in the deck. A histogram of the distribution of half-cell potentials for the northbound LMC spans in 1994 is shown in figure 30. Span 3 had the most negative potentials (most corrosive).

A summary of the half-cell potentials for the northbound LMC spans in 1997 is shown in table 52. Span 3 again has higher negative half-cell potentials than the other two spans. The average half-cell potential for Span 3 is −299 mV, compared to −249 mV for Span 1, and −193 mV for

Span 2. The average potential for Span 3 is over the threshold limit of 250 mV and the average for Span 1 is right at the threshold limit. The maximum half-cell potential for Span 3 is −652 mV, for Span 1 is −496 mV, and for Span 2 is −473 mV.

Table 50. Cumulative frequency of half-cell potentials for U.S. 41, SFC (SB travel lane 1997).

Potential Range (mV)	Number of Observations				Cumulative Percentage
	Span 1	Span 2	Span 3	Total	
0 to –49*	0	8	3	11	1.9
–50 to –99	0	101	39	140	26.6
–100 to –149	4	53	82	139	51.4
–150 to –199	45	15	41	101	69.0
–200 to –249	43	5	8	56	78.8
–250 to –299	47	6	6	59	89.2
–300 to –349	25	1	6	32	94.9
–350 to –399	18	0	4	22	98.8
–400 to –449	7	0	0	7	100.0
–450 to –499	0	0	0	0	100.0
–500 to –549	0	0	0	0	100.0
–550 to –599	0	0	0	0	100.0
–600 to –649	0	0	0	0	100.0
–650 to –699	0	0	0	0	100.0

* Note. Any positive reading is counted as 0 for tabulation.

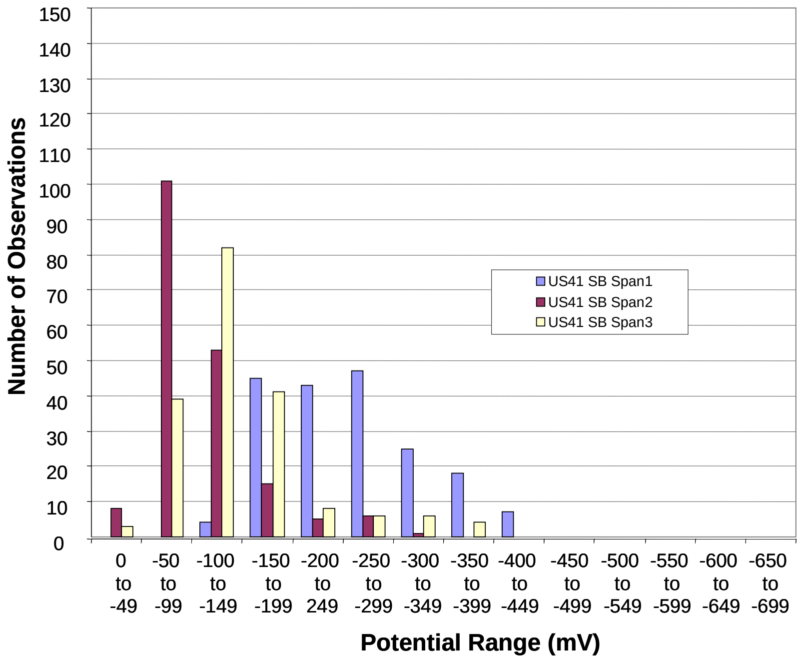


Figure 28. Histogram of half-cell potential readings for U.S. 41 southbound in 1997 SFC.

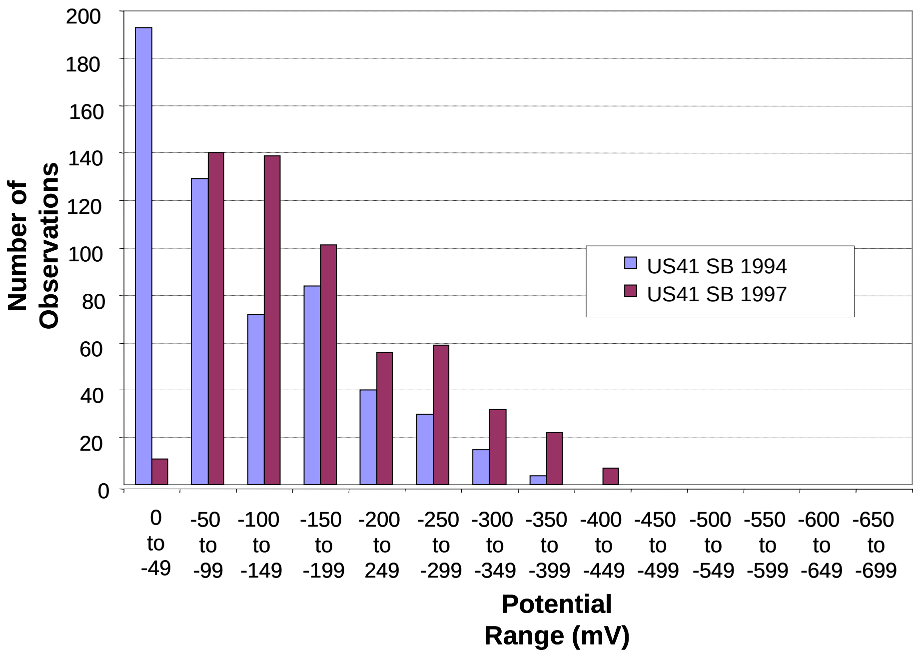


Figure 29. Histogram of half-cell potential readings for U.S. 41 southbound SFC in 1994 and 1997.

Table 51 Cumulative frequency of half-cell potentials for U.S. 41, LMC (NB travel lane 1994).

Potential Range (mV)	Number of Observations				Cumulative Percentage
	Span 1	Span 2	Span 3	Total	
0 to –49*	0	0	0	0	0
–50 to –99	0	6	0	6	1.0
–100 to –149	7	55	0	62	12.0
–150 to –199	54	78	12	144	37.4
–200 to –249	62	43	63	168	67.0
–250 to –299	37	5	57	99	84.5
–300 to –349	17	2	21	40	91.5
–350 to –399	11	0	19	30	96.8
–400 to –449	1	0	11	12	98.9
–450 to –499	0	0	6	6	100.0
–500 to –549	0	0	0	0	100.0
–550 to –599	0	0	0	0	100.0
–600 to –649	0	0	0	0	100.0
–650 to –699	0	0	0	0	100.0

*Note. Any positive reading is counted as 0 for tabulation.

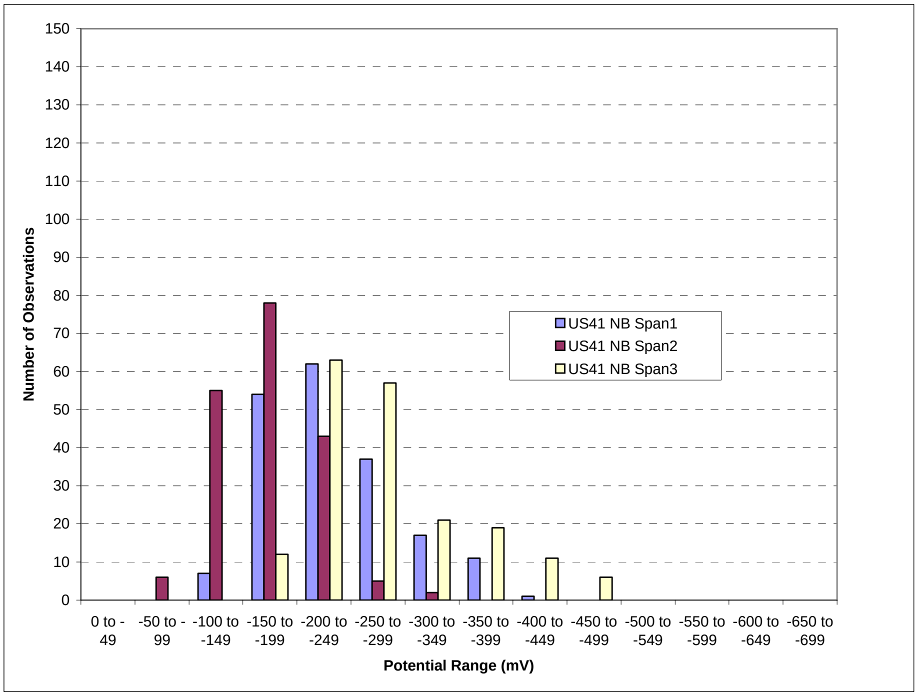


Figure 30. Histogram of half-cell potential readings for U.S. 41 northbound LMC in 1994.

Table 52. Cumulative frequency of half-cell potentials for U.S. 41, LMC (NB travel lane 1997).

Potential Range (mV)	Number of Observations				Cumulative Percentage
	Span 1	Span 2	Span 3	Total	
0 to –49*	0	0	0	0	0
–50 to –99	0	5	0	5	0.9
–100 to –149	18	33	0	51	9.9
–150 to –199	44	71	18	133	33.3
–200 to –249	49	64	47	160	61.6
–250 to –299	33	9	47	89	77.2
–300 to –349	14	4	38	56	87.1
–350 to –399	20	1	10	31	92.6
–400 to –449	5	1	14	20	96.1
–450 to –499	6	1	8	15	98.8
–500 to –549	0	0	5	5	99.6
–550 to –599	0	0	1	1	99.8
–600 to –649	0	0	0	0	99.8
–650 to –699	0	0	1	1	100.0

* Note. Any positive reading is counted as 0 for tabulation.

All three spans have a considerable number of half-cell readings above the −250 mV threshold for corrosion. A histogram of the half-cell potential readings for the northbound spans in 1997 is shown in figure 31. A histogram of the half-cell potential readings for the entire northbound structure in 1994 and 1997 is shown in figure 32. The distribution appears similar but the curve for 1997 is shifted to the right, indicating a probability of increased corrosion.

A cumulative frequency diagram for both test sections of U.S. 41 is shown in figure 33. The figure shows the shift to the right for both test sections. The shift in the curve for the southbound SFC spans is much greater than that for the northbound spans LMC. However, the northbound spans LMC had more negative values both initially and at the end of the study than the southbound SFC spans. An equipotential map of the half-cell readings for the southbound spans SFC of U.S. 41 is shown in figure 34. The figure for Span 1 indicates there is corrosion occurring along the edge between the travel and passing lane and at the two ends of the span. The figures for Span 2 and Span 3 indicate corrosion is occurring in isolated areas and also at the ends of the spans. An equipotential map for the half-cell readings for the northbound spans LMC is shown in figure 35. The maps for Span 1 and Span 3 indicate corrosion occurring over much of both spans and especially along the edge between the travel and passing lanes. The map for Span 2 indicates isolated areas of corrosion but most areas are at the ends of the span.

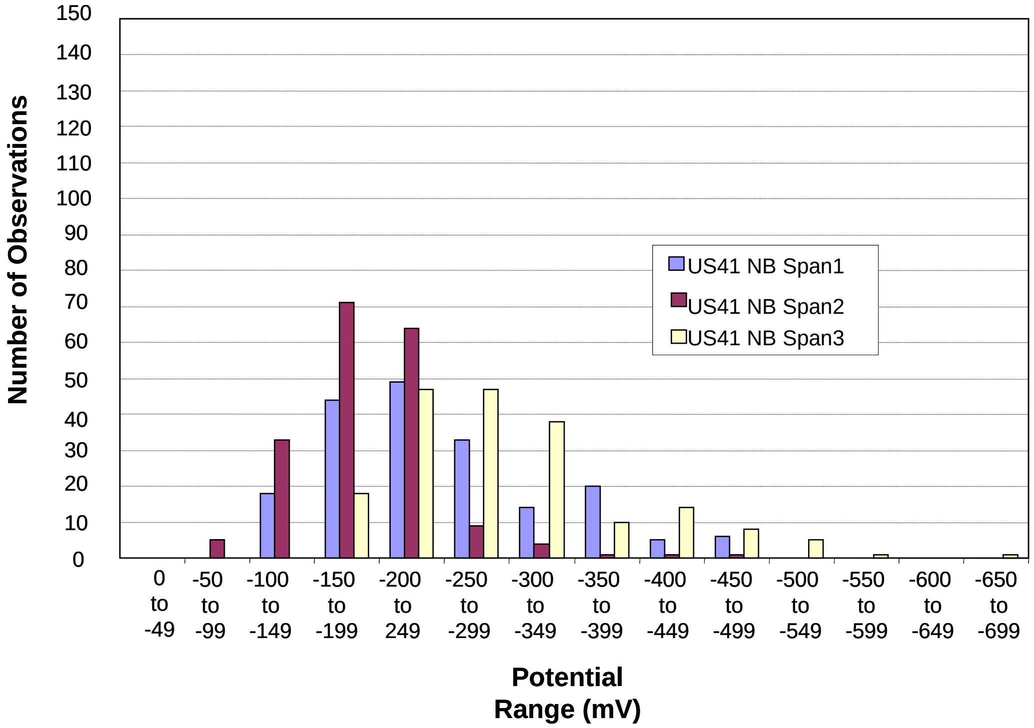


Figure 31. Histogram of half-cell potential readings for U.S. 41 northbound LMC in 1997.

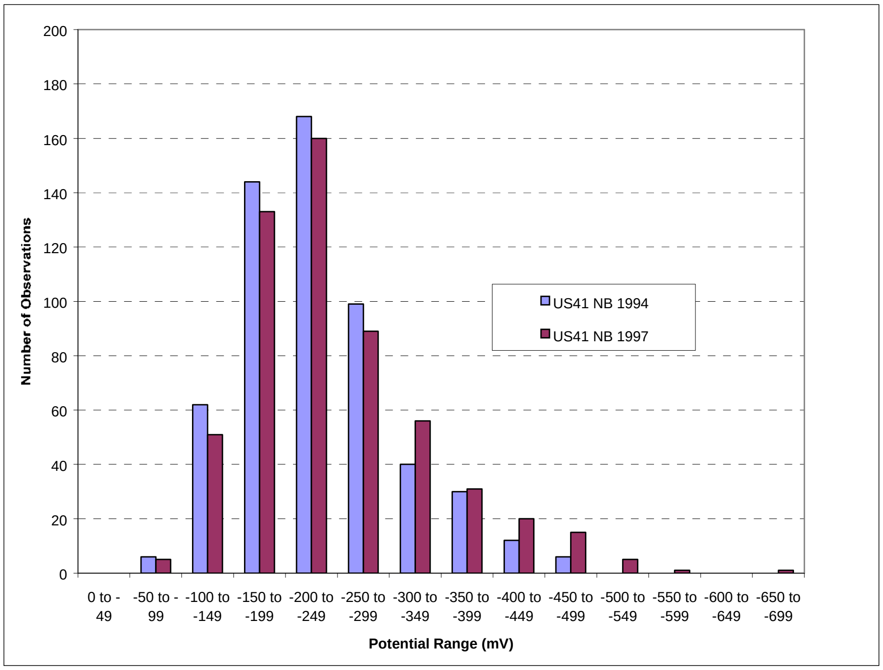


Figure 32. Histogram of half-cell potential readings for U.S. 41 northbound spans in 1994 and 1997.

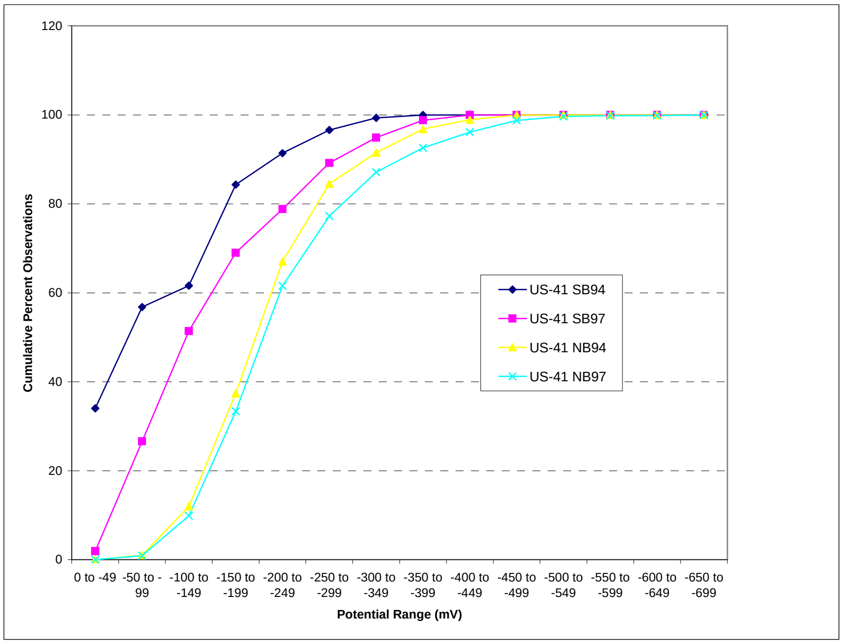


Figure 33. Cumulative frequency diagram for U.S. 41 (NB and SB) for years 1994 and 1997.

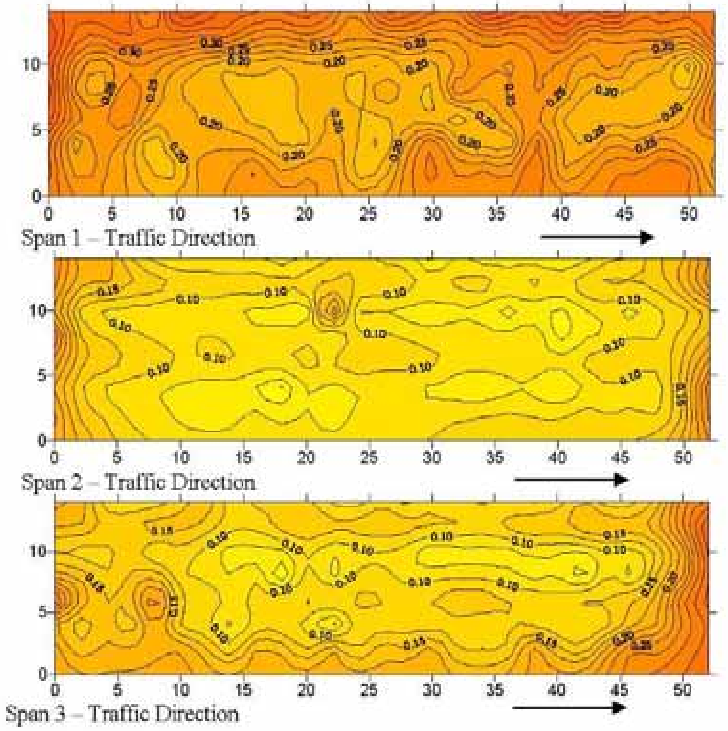


Figure 34. Equipotential maps of half-cell potentials for the three spans of the southbound test section of U.S. 41 in 1997 SFC.

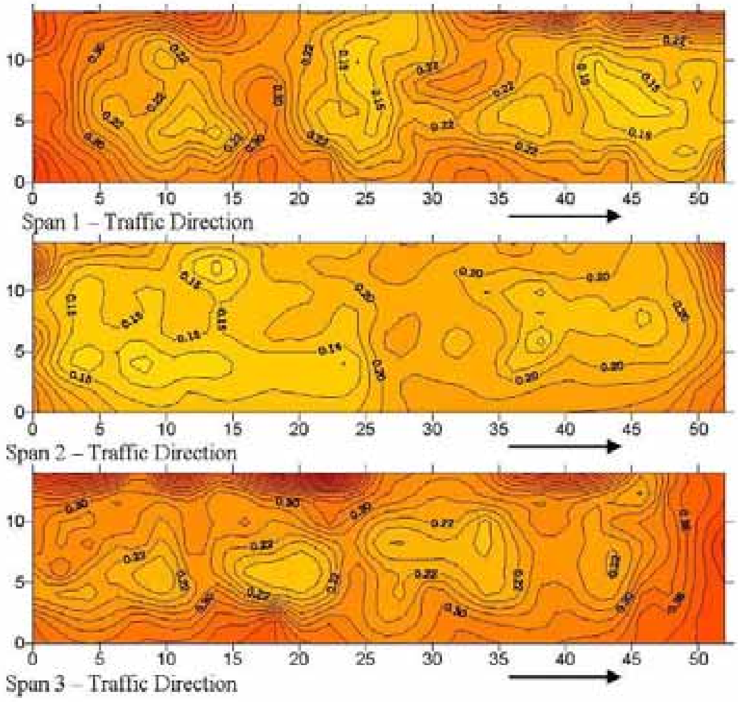


Figure 35. Equipotential maps of half-cell potentials for the three spans of the northbound test section of U.S. 41 in 1997 LMC.

POLARIZATION RESISTANCE (PR) TESTING

In 1994, the PR tests were performed using an EG&G PARC model 273A potentiostat under computer control. The PR scans were performed using IR compensation at each step to determine and correct for the potential drop due to the concrete resistance. The PR scans started at a potential 10 mV below the equilibrium "rest" potential of the area under test and continued to a potential 10 mV above the equilibrium potential. Following the testing, the polarization resistances were determined by fitting a line to the recorded potential versus current plots. Using the polarization resistances, the corrosion rates were estimated by assuming Tafel slopes of 0.12, assuming that the upper bars were size No. 4, and assuming that the upper half of the reinforcing bar directly under the counter electrode was polarized during the testing. Simulated 3LP tests were also performed at each of the test locations.

Following the half-cell potential testing, PR tests were performed at six locations on the southbound SFC spans. Two test locations were located on each span. The test locations on Span 2 had relatively low potentials while the locations on Spans 1 and 3 had moderate potentials. The PR and 3LP testing was generally more successful on the southbound SFC structure than on the northbound LMC structure. The results of the testing are summarized in table 53. On the southbound SFC structure, the corrosion rate measurements were not in general agreement with the half-cell potential measurements. The highest corrosion rates did not necessarily correspond to the most negative potentials. The agreement between the corrosion rates estimated using the two techniques was encouraging, as all of the estimates were within a factor of 2 or 3, which would generally be considered good using these techniques. Polarization resistance tests were also performed at six locations on the northbound LMC bridge. Two test locations were selected from each span. Only two of the six locations were successfully tested using the 3LP technique. The results of the testing are summarized in table 54.

Table 53. Corrosion rate testing on U.S. 41 southbound, SFC (1994).

Grid Location	Equilibrium	PR Testing		3LP Testing	
	Potential (mV)*	R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
Span 1, B4	–272	397	0.054	2571	0.008
Span 1, F4	–167	594	0.037	2449	0.009
Span 2, E5	–46	375	0.057	1587	0.013
Span 2, D4	–74	-	-	297	0.073
Span 3, D11	–130	732	0.03	489	0.044
Span 3, E11	–146	200	0.108	243	0.089

* Measured using a Cu/CuSO4 reference electrode.

Table 54. Corrosion rate testing on U.S. 41 northbound.

Grid Location	Equilibrium Potential (mV)*	PR Testing		3LP Testing	
		R_p (ohm)	I_{corr} (mA/cm^2)	R_p (ohm)	I_{corr} (mA/cm^2)
Span 1, C22	–251	475	0.046	-	-
Span 1, E22	–160	247	0.087	127	0.170
Span 2, C30	–320	26	0.834	-	-
Span 2, A30	–205	-	-	-	-
Span 3, D48	–315	400	0.054	145	0.150
Span 3, B48	–343	449	0.048	-	-

* Measured using a Cu/CuSO4 reference electrode.

The corrosion rate measurements were not in general agreement with the half-cell potential measurements, as the most negative potentials were associated with some of the lowest corrosion rates. The location with the least-negative potential, point A30, could not be successfully measured using either the polarization resistance or the 3LP technique. The very high corrosion rate observed at point C30 does not agree with the observed condition of the bridge.

In 1997, linear polarization measurements were performed at six locations on each structure. On each structure three locations were selected on Span 1, one was chosen on Span 2 and two were chosen on Span 3. More locations were chosen on Span 1 of each bridge because the half-cell potentials were generally higher. The testing was performed using a James Instruments GECOR 6 Polarization Resistance Tester. The results of the testing for both the southbound travel lane SFC and the northbound travel lane LMC-III are shown in table 55. There is considerable scatter in the corrosion rate measurements for both sections in 1997 but the corrosion rate measurements within a span generally coincide with the half-cell potentials within that span. Corrosion rates varied from low to moderately high on the SFC overlay and from low to moderately low on the LMC-III overlay.

Table 55. Results of polarization resistance testing at U.S. 41 (1997).

Direction	Span	Grid Location	Half-Cell Potential (mV)	Measured Corrosion Rate (µA/cm^2)	Notes
Southbound Travel SFC	1	A40	–348	0.147	More negative potential
	1	EF40	–218	0.930	Not confined, moderate potential
	1	C20	–161	2.368	Not confined
	2	C50	–134	0.056	Moderate potential
	3	A10	–154	0.042	Moderate potential
	3	EF10	–193	0.069	Moderate potential
Northbound Travel LMC-III	1	E17	–362	0.079	Relatively high potential
	1	BC9	–197	0.022	Two locations at same grid point,
	1	BC9	–197	0.022	Different concrete
	2	G50	–291	0.146	Moderately high potential
	3	DE20	–162	0.004	Low potential
	3	G29	–293	0.039	High potential

CORE TESTING

The cores were inspected to determine the overlay thickness and the cover over the uppermost reinforcing bars. The thickness of the silica fume concrete overlay on the southbound structure ranged from 25 to 100 mm (1 to 4 inches) and the depth to the top mat of reinforcing steel ranged from 65 to 90 mm (2.5 to 3.5 inches). The thickness of the latex-modified concrete overlay on the northbound structure ranged from 0.75 to 3.25 inches (19 to 83 mm) and the depth to steel ranged from 65 to 95 mm (2.5 to 3.75 inches). In 1994, three cores from each structure were tested for bond strength. The results are shown in table 56. The test results for northbound cores LMC are higher than the cores from the southbound structure SFC. The cores from the northbound LMC structure have a higher percentage of the failure occurring in the base concrete. Generally the bond strength of all the cores is quite high. This indicates both overlays were well bonded to the base concrete in 1994.

Table 56. Shear bond testing of cores from U.S. 41 (1994).

Overlay Type	Core ID	Bond Strength MPa (psi)	Failure Location (Percent of Failure Area)		
			Overlay	Bond Line	Substrate
Southbound Travel SFC	2	3.9 (574)	50	0	50
	4	2.6 (384)	25	25	50
	5	3.9 (565)	40	10	50
Northbound Travel LMC	3	4.9 (716)	40	0	60
	5	4.5 (649)	0	5	95
	7	4.4 (645)	20	0	80

In 1997, four cores from the southbound travel lane and three cores from the northbound travel lane were tested in shear. The results are shown in table 57. The average bond strength of the cores from the northbound travel lane LMC is slightly higher than that of the cores from the southbound travel lane SFC but the bond strength of all the cores is very good. This indicates that away from delaminations both overlays were still well bonded to the base concrete in 1997.

Table 57. Core Testing Results from U.S. 41 Henderson, KY (1997).

Location and Overlay Type	Core ID	Exposure Condition	Bond Strength MPa (psi)
Southbound Travel SFC	4	Wheel path	3.0 (430)
	5	Wheel path	3.6 (530)
	6	Wheel path	4.0 (580)
	7	Wheel path	4.7 (680)
	Average		**3.8 (555)**
Northbound Travel LMC-III	2	Wheel path	5.2 (750)
	3	Centerline	4.5 (650)
	10	Wheel path	3.4 (490)
	Average		**4.3 (630)**

CHLORIDE ANALYSIS

Following the visual examination of the cores, chloride analyses were performed on six cores taken from each overlay in 1994. The samples were taken from the 12- to 25-mm (0.5- to 1-inch) depth surface region and from the 70- to 89-mm (2.75- to 3.5-inch) depth where the reinforcing bars would have been located. All of the slices were then pulverized and analyzed to determine their acid-soluble chloride content. In addition to the acid-soluble chloride analyses, water-soluble chloride analyses were performed on selected samples. The results of the testing are shown in table 58. The levels of chloride in the overlays are generally very low and the levels in the northbound LMC overlay may be slightly higher than in the southbound SFC overlay.

Table 58. Results of chloride content testing of cores from U.S. 41 (1994).

Overlay Location and Type	Sample Number	Acid-Soluble Chloride Content, percent by concrete weight		Water-Soluble Chloride Content, percent by concrete weight	
		0.5 to 1 inch	2.75 to 3.5 inches	0.5 to 1 inch	2.75 to 3.5 inches
Southbound Silica Fume	S1	< 0.007	0.025	< 0.007	0.013
	S5	0.007	< 0.007	-	-
	S6	-	< 0.007	-	< 0.007
	S7	< 0.007	< 0.007	-	-
	S8	0.014	0.012	-	-
	S9	-	< 0.007	-	-
Northbound LMC-III	N4	-	0.061	-	-
	N5	-	0.045	-	-
	N6	0.039	0.008	-	-
	N7	< 0.007	0.037	-	-
	N8	0.010	0.017	-	-
	N9	-	0.017	-	0.011

All of the locations had low chloride concentrations at the level of the reinforcing bars, except for samples N 4 and N 5. The approximate threshold for chloride-induced corrosion of black reinforcing steel is approximately 0.025 percent by concrete weight, so most of the locations in the deck do not appear to have sufficient chloride to support corrosion.

In 1998, chloride water-soluble chloride contents were measured in five locations in the southbound SFC overlay and six locations in the northbound LMC overlay. The results are shown in table 59. The chloride levels down to a 25-mm (1-inch) depth in 1998 are elevated in the northbound LMC structure where many of the locations now have chloride levels above the 0.025 percent threshold. The acid-soluble chloride content was also measured on one core from each structure. The results are shown in table 60. The chloride level generally decreases with depth.

Table 59. Results of water-soluble chloride content testing of cores from U.S. 41 (1998).

Location and Overlay Type	Water-Soluble Chloride Content, percent by weight of concrete			
	0.25 to 0.5 inch	0.625 to 1 inch	1.125 to 1.5 inches	2.75 to 3.25 inches
Southbound SFC	0.005	0.004	< 0.004	0.009
	-	< 0.004	-	-
	-	0.004	-	-
	0.118	0.017	0.018	0.020
	-	0.012	-	-
Northbound LMC	0.139	0.096	0.060	0.044
	-	0.031	-	-
	0.116	0.059	0.030	0.024
	-	0.077	-	-
	0.041	0.012	< 0.007	0.011
	-	< 0.007	-	-

Table 60. Results of acid-soluble chloride content testing of cores from U.S. 41 (1998).

Location and Overlay Type	Acid-Soluble Chloride Content, percent by weight of concrete			
	0.25 to 0.5 inch	0.625 to 1 inch	1.125 to 1.5 inches	3.75 to 4 inches
Southbound SFC	0.048	0.010	0.035	< 0.007
Northbound LMC	0.070	0.010	< 0.007	< 0.007

SUMMARY OF U.S. 41 TEST (HENDERSON, KY)

The SFC and LMC-III overlays were placed in July and August 1992, respectively. Concern on the application of the bonding agent on Span 1 of the SFC and on the LMC-III overlays was expressed by State inspectors. Span 1 of the SFC overlay developed many large cracks. Spans 1 and 3 of the LMC-III overlay exhibited heavy transverse and longitudinal cracks while Span 2 had little cracking. Cracking generally increased with time. Delamination of the various spans within each test section, varied, with more delamination occurring in the end spans and less occurring in the center spans. The center span of the SFC overlay had no delaminations during the 5-year study. The average percent surface area that was delaminated was 3.7 percent for the SFC overlay and 18.2 percent for the LMC overlay.

Half-cell potentials also varied with span. Span 1 of the SFC overlay and Span 3 of the LMC overlay had more negative potentials than the other spans. However, the potentials were typically low to moderate. Table 61 summarizes the potential data.

Table 61. Potentials more positive than –250mV (Percent of measurements).

Year	NB (SFC)	SB (LMC-III)
1994	91.4	67.0
1997	78.8	61.6

The potentials shifted slightly more negative (corrosive) over the 5-year study. Local anodic areas were identified especially near joints and between lanes. Corrosion rates varied from low to moderate on both structures. Bond strengths away from delaminated areas remained high throughout the study. Chlorides have ingressed into the surface of the LMC-III overlay and into the SFC overlay to a lesser degree. The chloride at the level of reinforcing remains generally low.

CHAPTER 7. PROJECT SUMMARY

Evaluation and comparison of SFC and LMC-III overlays were performed at a total of four locations. The test sites were in Ohio and Kentucky. Each location included SFC and LMC-III overlays on opposite directions of a bridge structure. All overlays were installed in 1992. This study evaluated the overlays each year between 1994 and 1998. Table 62 summarizes the test data and observations for all test sites. All overlays had high initial bond strengths, and the bond strengths remained high over the study period when tested away from delaminations. The overlays were generally rated as good condition in 1998, after 6 years of service. However, both overlays at the U.S. 41 Henderson, KY site were rated as fair due to extensive cracking. Cracking was found in portions of the overlays at each site. Most of the cracking increased with time. However, some spans of each type were crack-free in 1998.

The percent delamination varied with test site. The U.S. 52 test site in Ohio had the least amount of delamination (less than 1 percent). The LMC-III overlay at U.S. 41 KY had the highest amount of delamination in 1989 with 18.2 percent. At I–270 in Ohio, both overlays had moderately high levels of delamination, about 7 percent.

The bridge at I–270 OH had the highest chloride in the existing deck and corrosion of the steel was likely before the overlays were placed. A high probability of corrosion was measured over most of the two I–270 decks in 1994. The potentials had shifted more positive in 1997 indicating that corrosion may be slowing slightly, with an additional 10 percent of both decks becoming more positive than –250 mV $CuCuSo_4$ half-cell potential. U.S. 41 KY, NB LMC-III may have had sufficient chloride in the original deck to initiate corrosion and had moderately high negative potentials in about one third of the deck (1994). The potentials of both overlays at this site have shifted more negative (corrosive) between 1994 and 1997. The remaining two sites, I–265 KY and U.S. 52 OH, had mostly positive potentials in 1994 and they did not shift significantly in 1997.

By 1998, the average (acid-soluble) chloride in the SFC overlays was 0.10 percent at 9.5 mm (0.375 inch) and 0.04 percent at 20.6 mm (0.8125 inch) depth. The LMC-III overlays were similar but slightly higher at 0.13 percent at 9.5 mm (0.375 inch) and 0.08 percent at 20.6 mm (0.8125 inch).

Good performance can be achieved from both SFC and LMC-III overlays. However, the service life of the overlays tends to vary based on the site location. While most of the overlays continue to provide good service after 6 years, the SFC and LMC-III overlays on U.S. 41 in Henderson, KY, show significant distress in the form of cracking and delamination. Significant repairs are needed for these two overlays. Generally, cracking and delamination of the overlays tend to increase with time. All overlays should be inspected bi-annually for cracking and delamination. Routine maintenance including crack and delamination repairs should be considered to extend the service life of the SFC and LMC-III overlays.

Table 62. Summary of all test sites.

Location	Type	General Condition (1998)	Cracking	Percent Delamination 1998 (m^2)	Potentials More Positive Than –250 mV			Chlorides Exceed Threshold Prior to Overlay ? (water-soluble)	Average Chloride in Overlay (1998) (acid-soluble) %	
					1994	1997	Difference		0.25 to 0.5 inch	0.625 to 1 inch
I–270 NB, OH	SFC	Good-Fair	Yes	6.60	14.2	24.1	+ 9.9	Yes	0.14	0.03
I–270 SB, OH	LMC-III	Good-Fair	Yes	7.00	1.7	13.1	+ 11.4	Yes	0.24	0.13
U.S. 52 WB-P, OH	SFC	Good	Yes-Minor	0.87	-	96.8	−	No	0.10	0.07
U.S. 52 EB, WB-T, OH	LMC-III	Good	Yes	0.14	98.8	97.3	−1.5	No	0.13	0.09
I–265 SB, KY	SFC	Good-Fair	Yes	4.50	85.6	86.5	+ 0.9	Maybe	0.11	0.04
I–265 NB, KY	LMC-III	Good	Yes-Minor	0.90	98.2	98.4	+ 0.2	Maybe	0.08	0.05
U.S. 41 SB, KY	SFC	Fair	Yes	3.70	91.4	78.8	−12.6	No	0.06*	0.01*
U.S. 41 NB, KY	LMC-III	Fair	Yes	18.20	67.0	61.6	− 5.4	No-Maybe	0.09*	0.04*
Average	**SFC**	**-**	**-**	**3.90**	**63.7**	**71.5**	**+ 7.8**	**-**	**0.10**	**0.04**
Average	**LMC-III**	**-**	**-**	**6.50**	**66.4**	**67.6**	**+ 1.2**	**-**	**0.13**	**0.08**

* Average of acid- and water-soluble data.

Recycled
Recyclable